THE UNIVERSITY OF ALBERTA

A MODEL STUDY OF AN ISOLATED NORMAL FIVE SPOT

by

J.W. SERRA

A THESIS

SUBMITTED TO THE FACULTY OF GRADUATE STUDIES

IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE

DEGREE OF MASTER OF SCIENCE

IN

PETROLEUM ENGINEERING

FACULTY OF ENGINEERING

DEPARTMENT OF CHEMICAL AND PETROLEUM ENGINEERING

EDMONTON, ALBERTA

AUGUST, 1966

THE UNIVERSITY OF ALBERTA

A MODEL STUDY OF AN ISOLATED NORMAL FIVE SPOT

by

J.W. SERRA

A THESIS

SUBMITTED TO THE FACULTY OF GRADUATE STUDIES

IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE

DEGREE OF MASTER OF SCIENCE

IN

PETROLEUM ENGINEERING

FACULTY OF ENGINEERING

DEPARTMENT OF CHEMICAL AND PETROLEUM ENGINEERING

EDMONTON, ALBERTA

AUGUST, 1966

UNIVERSITY OF ALBERTA

FACULTY OF GRADUATE STUDIES

The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies for acceptance a thesis entitled A MODEL STUDY OF AN ISOLATED NORMAL FIVE SPOT submitted by J.W. Serra in partial fulfilment of the requirements for the degree of Master of Science in Petroleum Engineering.

ABSTRACT

One of the major factors contributing to the success or failure of a secondary recovery project is the fraction of the reservoir contacted by the recovery mechanism. Analysis of the behavior of a pattern waterflood can best be studied by the use of scaled flow model studies.

The contribution of the area swept out beyond the normal well pattern is of prime importance in a pilot waterflood study. In addition, in predicting the sweep out pattern efficiency to be expected in a secondary recovery operation, the reservoir engineer is often confronted with a situation in which part of the producing formation lies between the last row of wells and the reservoir boundary. To date, there has been little reference in the literature to sweepout pattern efficiencies in such areas.

The performance of a single normal five-spot flood pattern was investigated to determine the effect of back pressure on the production performance and sweepout patterns. A scaled model employing a glass bead pack as the reservoir was used. Flood patterns were traced using fluorescent dyes excited by ultra-violet light.

It was found that surprisingly large portions of the reservoir area lying outside the pilot area are contacted by the injected fluid before abandonment conditions are reached.

ACKNOWLEDGEMENTS

The author wishes to acknowledge with sincere appreciation the cooperation and assistance he received from the Department of Chemical and Petroleum Engineering. In particular, a thank you is extended to Dr. D.L. Flock, Professor of Petroleum Engineering, under whose guidance the project was carried out.

In addition, the author expresses his appreciation for the cooperation and patience of the members of the staff of the shop and stores of the Chemical and Petroleum Engineering Department.

Acknowledgement is made to the National Research Council and Canadian Bechtel Ltd. for their financial assistance.

A debt of gratitude is certainly due my wife, whose cooperation and encouragement was a definite aid in completing this project.

TABLE OF CONTENTS

LIST OF FIGURES

INTRODUCTION

In most oil reservoirs the percentage of oil recoverable by primary means is quite small. Secondary recovery methods of many different types have been devised to increase the amount of oil recovered. A number of these methods depend upon the injection of a fluid into the reservoir, water flooding by water injection being the most common.

The efficiency of a flooding operation is usually measured in terms of the volume of oil displaced by the encroaching fluid. If the oil and the fluid are assumed incompressible and immiscible,the quantity of oil displaced is proportional to the area swept out by the injected fluid. In field pattern flooding the displacing fluid is injected and the oil is produced through wells which are, area wise, small openings in a large container or reservoir of oil. As a result, not all of the area between the injection and producing wells is necessarily contacted by the injected fluid by the time it first reaches the producing well. In predicting oil recovery the question arises as to what fraction of the pattern area involved is contacted by the injected fluid due to the relative position of the injection and producing wells. This is the areal sweep efficiency.

The flow of liquids through porous media is known to follow Darcy's Law which states that the velocity of flow is proportional to the potential gradient. This combined with

the continuity equation enables one to outline the problem mathematically. Early workers soon discovered that given this basic law of flow it was possible, theoretically, to obtain solutions to any problem of viscous flow of dead liquids by the usual methods of potential theory, providing that the mobility ratio* is one. However, problems of practical interest often presented such complex geometrical configurations of sources and sinks as to make the analytical solutions extremely difficult or even impossible. Hence, model studies of various kinds were employed to overcome the analytical problems.

In the subject study, a program of scaled flow model experiments was undertaken to study the performance of an isolated normal five-spot water flood. The tests were specially designed to study the effect of back pressure on the flooding performance. Of particular interest was the oil recovered from the region outside the normal well pattern.

The flow model experiments described simulate a uniform, horizontal formation of constant thickness with fully penetrating wells. The system under consideration is entirely liquid saturated and not influenced by compressibility effects. This is representative of the situation achieved after gas fill up under practical conditions. Gravity segregation ef-

---

* The definition of this term follows in a later section.

fects are assumed to be negligible, which implies a relatively thin reservoir formation and/or low vertical permeability.

LITERATURE SURVEY

Model Studies

The problem of determining what portion of the reservoir is contacted by an injected fluid has been approached in a variety of ways. In addition to the mathematical approach, several types of models have been used to study oil and gas reservoir performance. These models may be classified as physical, electrolytic, potentiometric, X-ray shadowgraph, and fluid mapper.

One of the earliest workers in this field, Muskat(42,44), obtained mathematical solutions to the problem for some of the simpler configurations assuming Buckley Leverett type displacement(9) and a mobility ratio of one. However, problems with complex geometrical configurations or mobility ratios other than one could not be solved analytically by his technique.

Muskat, Wyckoff, and Botset(62) noting that the steady state flow of liquids is analagous to the potential distribution in an electrical conducting medium developed the electrolytic model. The model depended upon the movement of OH ions from the negative to the positive terminal in an electrolyte saturated porous media. Subsequently, several authors used this model(7,8,40,54,62). One of the biggest faults of this model was the fact that diffusion of the ions resulted in a loss of sharpness in the boundaries making the results inaccurate.

Hurst and McCarty(32) developed an electrical conduction model based on the same analogy but using a conducting liquid in a pool, the bottom of which was shaped to account for varying thickness of the reservoir. In their method the calculation of a line integral was required. This often presented mathematical difficulty. Lee(34) modified the method to eliminate this difficulty by direct plotting and graphical solutions. Potentiometric models of this type with slight variations became the accepted method of conducting areal sweep efficiency studies. Several authors in the literature used this technique(2,3,32,34,37,41,42).

Numerical methods were introduced by Fay and Prats(25) to determine the invasion patterns. Their methods did not gain a wide acceptance. This could be partially due to the fact that they required high speed computers which were not readily available at that time.

A gelatin model, which could account for varying mobility ratio, was proposed by Burton and Crawford(10) while Noble and Jansen(47) used a resistance network analog. These methods did not gain to much popularity.

Slobod and Caudle(60) introduced radiographic techniques to determine sweep-out factors for any type of well spacing. In this method the location of various phases distributed over a test area are observed simultaneously by obtaining a photographic record of the transmission of X-rays

through the test plate. At present this is the most widely accepted technique as it is readily adaptable to a number of models.

Among the many models used in conjunction with X-ray techniques are the fluid mapper model which consists of two thin plates spaced a few thousandths of an inch apart and model packs employing various materials to simulate the reservoir. Slobod and Caudle(60) used fused alundum, Rappaport, Carpenter, and Lea's(56) used glass beads, and Craig, Geffin and Morse(17) used actual reservoir rock slabs.

Numerous papers outlining the effect of mobility ratio and other parameters on sweep efficiency prior to break-through were published(2,3,10,15,17,22,47,60). However, little emphasis was placed on the period after the initial break-through by these earlier workers.

Dyes, Caudle, and Erickson(23) extended the study of the influence of fluid mobilities to cover the production period following break-through of the injected fluid. They used miscible fluids and X-rays shadowgraph techniques. Craig, Geffin, and Morse(17) further investigated the period after break-through considering mobility ratio effects and the effect of the volume of water injected. Their results agreed with the results found by Dyes et al(23) for the areal sweep efficiency at break-through for various mobility ratios.

The work to this point had concerned itself with confined patterns only. Pilot water flooding operations were

common practice by this time and since a pilot flood is normally an unconfined pattern, the results from the confined floods could not be applied. Hence, studies on unconfined pattern floods were initiated.

Caudle, Erickson and Slobod(12) investigated what occurred in the area beyond the normal well pattern and found that at least 90% of the area lying outside the last row of wells within one well spacing of these wells would ultimately be contacted by the injected fluid. The system studied by these authors consisted of a number of confined five-spots in a fully developed pattern plus the area, within one well spacing, beyond these patterns. The total area of this system was divided into symmetrical sections. It was found that there were three re-occurring shapes. A model of each of these shapes was built and the performance of each was studied. By combining the performance of each of these shapes and weighing their contribution to the overall performance by the number of times the shape appeared in the overall pattern, the authors were able to calculate the overall performance. Using various combinations of these three shapes, a number of different patterns could be formed. At a mobility ratio of 1/3, using the pattern which most closely resembled a single normal five-spot, the area contacted up to a water-oil ratio of 19 to 1 was found to be approximately 10 times the five-spot area.

Fischer-Rosenbaum and Matthews(26) also conducted studies on unconfined patterns to determine what information could be obtained from pilot water floods. Their object was to find an optimum pilot pattern for a reservoir which had previously been depleted by a solution gas drive. Their findings indicated that a single pattern flood would not give representative data.

Pilot water flood studies were also conducted by Dalton, Rappoport and Carpenter(21). Their work showed that the behavior of an unconfined pilot water flood could be characterized or scaled on the basis of a dimensionless parameter, the π ratio. This pressure parameter defined the operating conditions by expressing the ratio of the pressure drawdown at the producing well to the pressure build-up at the injection wells relative to the reservoir pressure. In all cases studied by them, the oil recovery and the total fluid production relative to cumulative injection were found to increase with increasing values of the π ratio. Areal recovery factors of up to 2 were encountered for some of the flood patterns. The areal recovery factor being defined as the ratio of the area which supplied oil to the pilot producers divided by the basic pilot pattern area.

Neilson(46) investigated the performance of an isolated inverted five-spot pattern at a constant mobility ratio. His findings show that approximately six times the pattern area was contacted by water up until a producing water-oil

ratio of twenty to one.

Several authors have studied the performance of five-spot floods*. Most of the studies were conducted on one quarter of a five-spot ignoring the area outside the pattern. Matthews and Fisher(38) studied the effect of dip on five-spot performance. Hurst presented a mathematical calculation procedure for determining the performance curve in five-spot water floods. His analysis did not consider the area outside the pattern area.

Craig(19) conducted studies to determine the influence of the effective productivity of the producing wells on the oil recovery efficiency of five-spot pilot floods as well as single injection well pilot floods. The effective productivity is indicated by the value of the condition ratio, defined as the ratio of the actual well productivity to that of an undamaged and non-stimulated normal sized well in the same formation. Experiments conducted at three different mobility ratios showed no difference in performance. Above a condition ratio of 2.22 the amount of oil recovered was in excess of 90% of the recoverable oil within the five-spot pattern. No consideration was given to the area outside the normal well pattern in this paper.

The difference between a confined flood and an unconfined pilot flood for a normal five-spot pattern was studied

---

* See references 3, 12, 13, 14, 15, 17, 18, 19, 20, 21, 22, 23, 52, 53, 56, 60.

by Caudle and Loncaric(14). The study was conducted on one quarter of a five-spot utilizing the geometric symmetry of the pattern. Studies were carried out at several mobility ratios and several rate ratios. The rate ratio is the ratio of the injection rate to the withdrawal rate. Oil production up to four times the displaceable five-spot pore volumes was obtained for the lower mobility ratios.

Culham(20),studying an isolated nine-spot obtained sweep-outs of up to eight times the pattern area at a water oil ratio of twenty-five to one. Paulsell(48), studying a five-spot pattern with a free-gas saturation, obtained areal sweepouts of up to 2.5 times the pilot area for the lower mobility ratios after 4 pore volumes of injection had taken place. Most of the studies to date which have dealt with unconfined patterns agree with these results; that is, the contribution from outside the well pattern is significant.

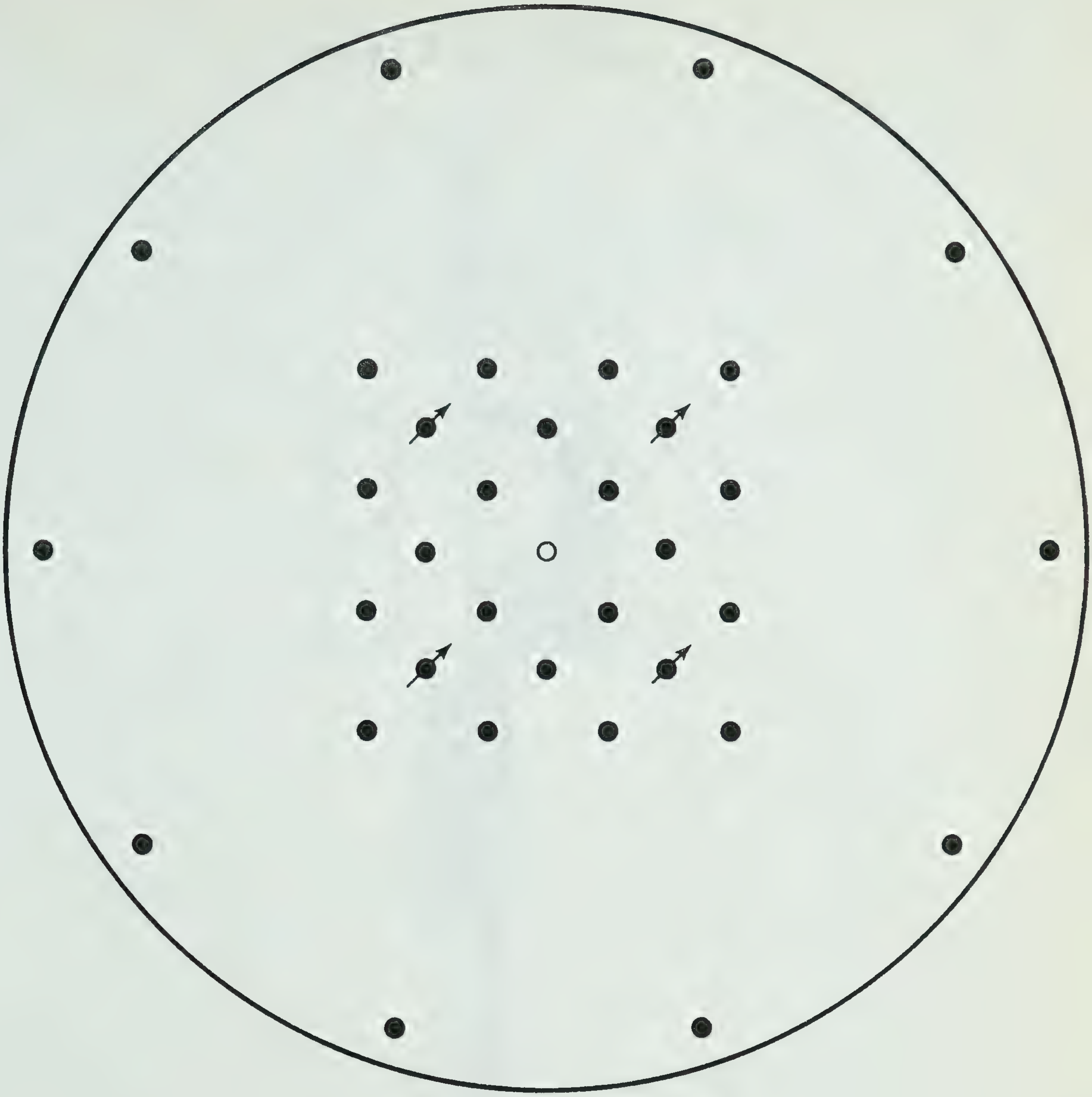
DESCRIPTION OF APPARATUS

The model consisted of a glass bead pack sandwiched between two transparent lucite plates. These lucite plates were circular with a diameter of three feet and were two inches thick. Separated by a one-quarter inch thick spacer and sealed by two neoprene O-ring seals, these plates were bolted together around the periphery. The glass beads, .6 mm. in diameter, were fed into the model through a hole in one end.

It was desirable to keep the reservoir thickness as small as possible to minimize the gravitational effects, however, it had to be large enough that the difference in wettability at the lucite faces would not affect the results appreciably. A rule-of-thumb accepted in model work is that the thickness must be larger than ten bead diameters. Hence, a reservoir thickness of 1/4 inch was used.

Ten simulated oil wells were located around the periphery of the model to allow for cleaning and evacuating of the model. A schematic diagram, Figure 1, shows the location of these wells. The pattern area of the model contained twenty-five more simulated oil wells arranged in the pattern shown in Figure 1. This enabled one to use many different patterns as well as many different sizes of any one pattern.

A scale drawing of the oil wells, machined from brass, is shown in Figure 2. The production tubing of the wells was



o PRODUCTION WELL

INJECTION WELL

SHUT-IN WELL

FIGURE 1

Scale: Twice Size

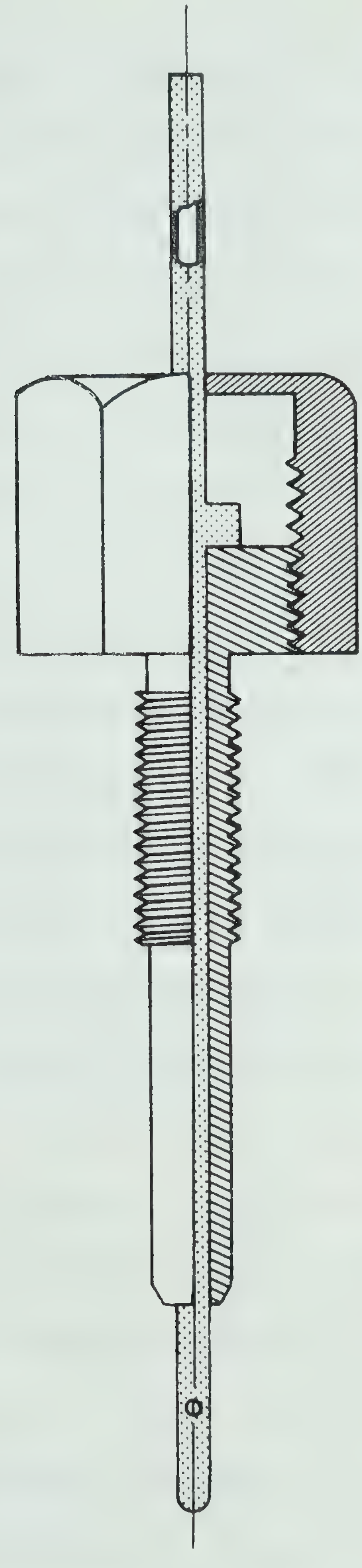


FIGURE 2

a stainless steel line with an inside diameter of 52/1000 of an inch and an outside diameter of 72/1000 of an inch. The lower end of the tubing was sealed and a 45/1000 of an inch hole was drilled through the tubing a short distance from this end. The wells could be closed off or turned on by raising or lowering this tubing so that the hole lined up with the formation or with a neoprene O-ring which seals the seat of the brass well.

The injection system consisted of four pistons mounted so that a fifth double acting piston could drive them forward or backward at the same constant rate. The double acting piston was operated hydraulically by a constant rate ruska pump. The injection pressure of each of the four injection streams was measured on a liquid filled manometer. The reservoir pressure was measured on a liquid filled manometer attached to one of the peripheral wells. The back pressure on the system was controlled by raising or lowering the production line outlet.

Injection patterns were traced by means of a water soluble fluorescent dye (Dupont Uranine B). The dye was made to fluoresce by means of ultra violet lamps, mounted beneath the model. A schematic diagram of the equipment is shown in Figure 3. In addition to Figure 3, a photograph of the entire apparatus appears in Figure 4.

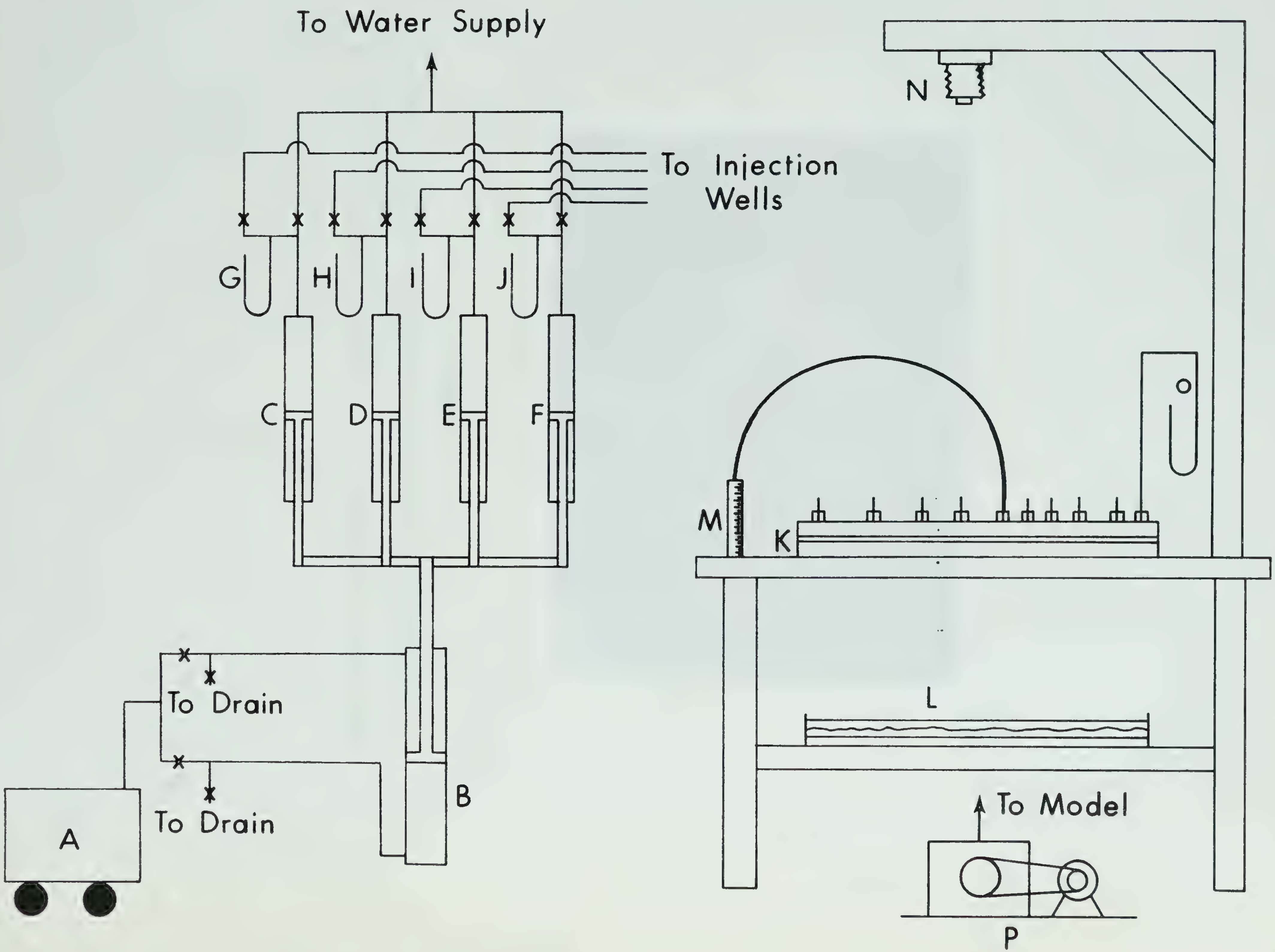

To Water Supply
To Injection Wells
G
H
I
J
C
D
E
F
To Drain
To Drain
A
B
N
O
M
K
L
To Model
P

FIGURE 3

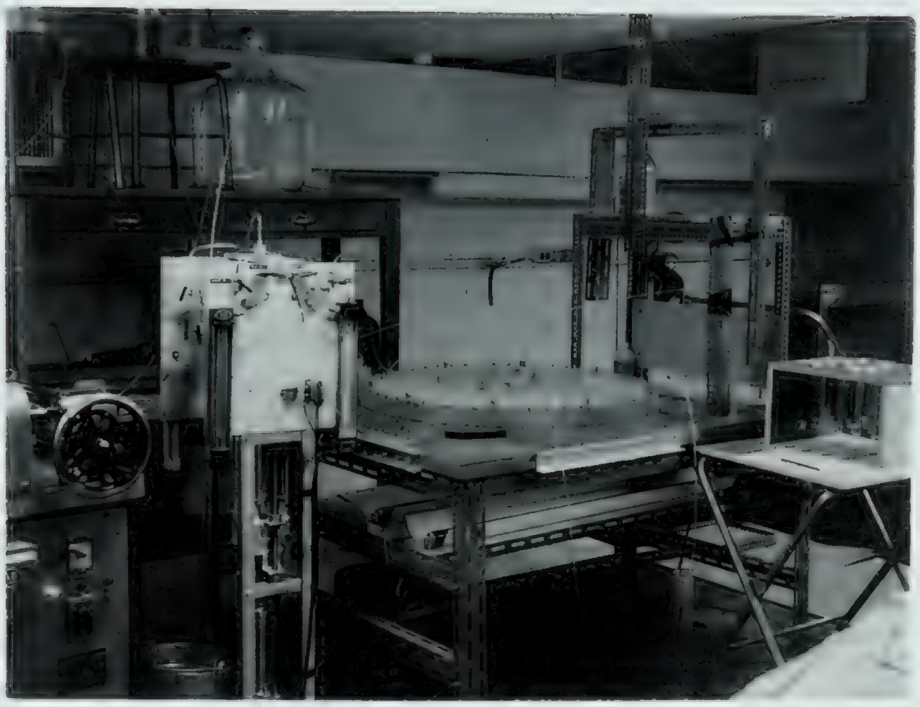


FIGURE 4

PHOTOGRAPH OF EQUIPMENT SHOWING TWO-DIMENSIONAL MODEL, INJECTION SYSTEM, AND LIGHTING ARRANGEMENT

PREPARATION OF THE MODEL

Considerable difficulty was encountered in attempting to pack the glass beads into the model. The model was bolted together and an attempt was made to feed the glass beads into the model from a hole in one end. Electrostatic forces between the beads caused them to repel each other to the extent that a uniform tight pack could not be attained. Wetting the beads before they were placed into the model reduced the repelling effect but caused the beads to cluster. The clusters adhered to the sides of the model preventing more beads from entering.

The next technique adopted consisted of saturating the model with a soapy water solution. The beads, also saturated with the soapy solution were then fed into the model. This reduced the clustering effect and eliminated the repelling forces between the beads. In this manner the model was packed to a reasonably tight pack.

However, in order to get a uniform maximum density pack it was necessary to vibrate the model on edge for a number of hours while the faces of the model were gently tapped with a soft headed hammer. It was found that in order to get the beads to pack most readily it was necessary to alternately saturate the model with water, then dry it completely, and vibrate it for a number of hours at each conditions. In all the model was vibrated on edge for over three hundred hours. The result was a maximum density, uniform porosity pack.

THE PATTERN

The pattern chosen to be studied was a normal isolated five-spot. Where a normal five-spot is defined as four injectors, one producer. Five-spots, either normal or inverted, are one of the most commonly used injection patterns. A water flood normally consists of an array of identical well patterns. In such an array, the perimeters of the well patterns are axes of symmetry, and act as impermeable boundaries. Thus, an extensive pattern water flood can be visualized as an aggregation of confined floods. In contrast, an isolated or pilot flood involves only one pattern and is unconfined. In the case of an unconfined flood the well pattern is not balanced by other flood units, hence, the perimeter of the pilot area does not act as an effective boundary. This causes the amount of oil and water produced in an isolated pattern to be different from that produced in an extensive flood.

The bulk of the work done on five-spot efficiencies has been done using one quarter of a pattern, thus utilizing the fact that the four quadrants are symmetrical. The model in such a case reduces to a square with a producer at one corner and an injection well at the diagonally opposite corner. Thus, the normal and inverted five-spots in a confined case reduce to the same thing. This model represents the performance of an internal five-spot in a fully developed pattern.

Pilot floods, on the other hand, generally consist of a single pattern operating in a larger area to determine economic feasibility of overall flooding and are thus unconfined. A second region where the unconfined flood becomes important is in the area closest to the boundary of the reservoir. The question often arises as to how close to the boundary should the first row of injectors be in order to sweep out the complete reservoir. The most common practice has been to place these wells very close to the boundary.

CALCULATION OF MODEL PROPERTIES

Porosity

Porosity may be defined as that fraction of the bulk volume of a material that is not occupied by the solid framework of the material(51). Porosity is thus a measure of the space available for fluid occupancy. Because not all of the void spaces may be interconnected it is advantageous to define effective porosity as being the percentage of interconnected void space with respect to the bulk volume.

Two methods were used to determine the effective porosity of the model. The first and most widely used in model studies is a simple material balance technique. The bulk volume of the model was determined from the physical inside dimensions of the model, while the void volume was obtained by evacuating the model and then saturating the pore spaces with water. The volume of fluid required to fill the model equals the void volume of the model. Effective porosity is the ratio of the void volume to the bulk volume. Calculation of porosity by this method is shown in the appendix in Table 1 and was found to be 33.2%.

The second method used to calculate the porosity was a method proposed by Paulsell(48). Considering any swept out area before breakthrough,the amount of fluid injected must be equal to the area swept out times the thickness of the porous medium multiplied by the porosity fraction. Calculations for

this method are given in Table 2 of the appendix. The method yielded a porosity of 32.1% which compares quite favorably with the porosity found by the first method.

A review of the literature published on model studies showed that most authors using spherical particles of a uniform size obtained porosities between 36 and 43%. The minimum possible stable porosity which can be obtained is 25.9% and represents rhombohedral or face centered cubic packing. This seems to indicate that the pack obtained in this model is exceptionally good and is probably due to the long period of time over which the model was vibrated.

Permeability

The permeability of a porous medium may be defined as its fluid conductivity(16), or its ability to let fluid flow within its interconnected pore network(51).

The quantitative expression for permeability known as Darcy's Law is as follows:

$$Q = -\frac{K}{\mu} A \operatorname{grad} \Phi$$

where

K = permeability in darcies

Q = flow rate in cc per sec.

Φ = pressure force potential

A = cross sectional area available for flow

μ = viscosity in centipoises

The permeability of a porous medium is a property of the porous medium and not of the fluid which flows through it, provided that the fluid 100% saturates the pore space of the rock and there is no movement between the fluid and the boundary of the system. This permeability at 100% saturation of a single fluid is called the absolute permeability of the rock.

In the case where the porous medium contains more than one fluid phase, the permeability can no longer be considered an invariable quantity, uniquely and completely fixed by the nature and structure of the porous medium. The permeability to each of the phases present must be considered. Flow of one fluid will be restricted by the presence of the other fluid. Thus, one may define the effective permeability to be the permeability of a porous medium to a particular fluid when that fluid has a pore saturation of less than 100%.

The effective permeability of the model to the two fluids was calculated using Muskat's five spot formula(43). The calculations are given in Tables 3 and 4 of the Appendix. The effective permeability to water, measured at the residual oil saturation of the model, 0%, was found to be 837 md. At a water saturation of 39%, the connate water saturation of the model, the effective permeability to oil was found to be 135 md.

Mobility Ratio

The most widely accepted definition for mobility ratio is the mobility of the displacing phase divided by the mobility of the displaced phase. The mobility of a fluid may be defined as the ratio of the effective permeability of the porous medium to the viscosity of the fluid. In the case of the system being studied, the mobility of the displacing phase (water) was found to 938 millidarcies per centipoise while the mobility of the displaced phase (oil) was found to be 290 millidarcies per centipoise. Hence, the mobility ratio of the system was calculated to be 0.324. Details of the calculation of the above figures appear in Table 6 of the appendix.

Wettability

Wettability, qualitatively speaking, denotes the ease with which a fluid can displace other fluids, or spread over a solid surface in the presence of other fluids(59). A quantitative definition of wettability is difficult to state. For this reason resort is made to relative wettability.

In the case of a porous medium, the concept of relative wettability has the following meaning. Of two fluids, one will generally wet the porous medium preferentially to the other; in other words, one fluid (the preferentially wetting one) will penetrate into a porous medium in preference

to the less wetting phase. The adhesion tension, which is a function of the interfacial tension, determines which fluid will preferentially wet the solid. A sketch is shown in Figure 5, wherein two liquids, oil and water, are in contact with a solid surface.

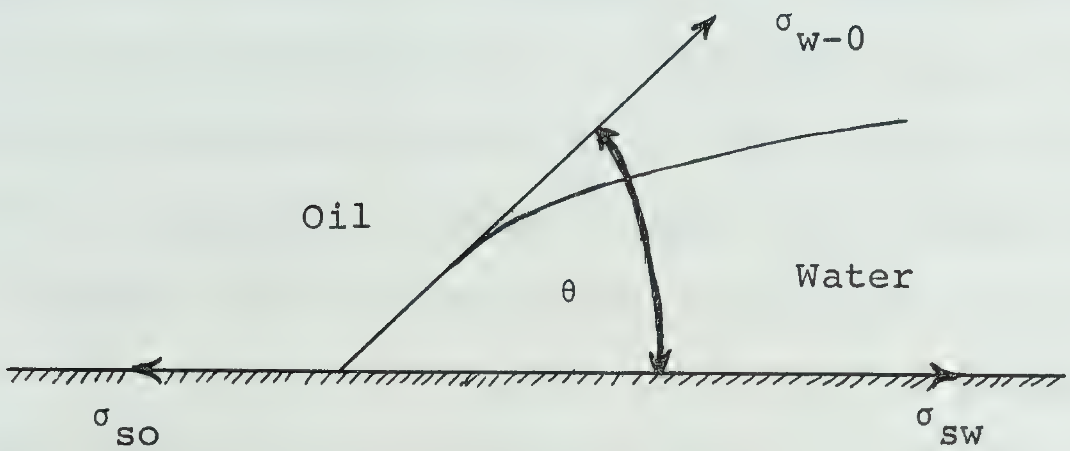


Figure 5

By convenction, the contact angle theta (θ) is measured through the denser liquid phase and ranges from 0° to 180°. Based on this convention the adhesion tension is defined by the following equation:

$$A_T = \sigma_{so} - \sigma_{sw}$$

$$= \sigma_{wo} \cos \sigma_{wo}$$

where A_T is the adhesion tension, σ_{so} is the interfacial tension between the solid and the oil, σ_{sw} is the interfacial

tension between the solid and the water, and σ_{wo} is the interfacial tension between the fluids. A positive adhesion tension indicates that the water phase preferentially wets the solid. The magnitude of the adhesion tension determines the ability of the wetting phase to adhere to the solid and to spread over the surface of the solid. No specific quantitative scale for reporting wettability is available as yet; however, the values of adhesion tension (A_T), cos θ, or the contact angle (θ) are generally used as indices of wettability.

A number of tests have been outlined in the literature to obtain an indication of the wettability of a porous media. Imbibition tests which consist of immersing a fluid saturated porous medium into another fluid and measuring the rate at which the original fluid is displaced have been outlined by Bobek, Mattax and Denekas(6). Imbibition tests conducted on a sample of the porous medium used in this project showed that neither of the fluids would displace the other fluid. However, lack of imbibition does not necessarily indicate nonwetting of the displacing phase(11).

A second technique, proposed by Bartell and Osterhof(5) concerns itself with the measurement of displacement pressure. The higher the displacement pressure required to force one fluid against another into a porous medium, the smaller is the wettability by that fluid.

The method used for determining the wettability of the system was a method outlined by Singhal(59). A modifica-

tion of the technique outlined by Bartell and Osterhof(5), the method concerns itself with the measurement of the displacement pressure.

Since wettability measurements are not absolute but relative, a standard of comparison was necessary. Singhal elected to use a pack of the cleanest possible beads as a reference. An apparent contact angle concept was used by him based upon the assumption that the cleanest possible surface had 0^{o} contact angle. The relationship used was:

$$\cos\theta = \frac{P_{co}}{P_{cr}} \cdot \frac{\sigma_{ow-r}}{\sigma_{o-wo}} \sqrt{\frac{K_o \phi_r}{K_r \phi_o}}$$

where

θ = apparent contact angle

P_c = displacement pressure

σ_{ow} = interfacial tension

K = permeability

ϕ = porosity

and the suffixes o and r refer to the properties of the sample under consideration and the reference sample, respectively.

The calculation of contact angle by this method appears in Table 7 of the Appendix and was found to 19^{o}, indicating a water wet system.

FLUID PROPERTIES

The values of the physical properties reported in this section were determined by the following methods. The densities were determined by weighing a known volume of each of the fluids. Following the procedure as outlined in ASTM Standards on Petroleum Products and Lubricants(4), the viscosities were determined using a Cannon-Fenske Viscometer while the interfacial tension between the oil and water was found using the ring method as outlined in the ASTM Standards on Petroleum Products and Lubricants(4).

Connate Water

The water used in the establishment of the connate water saturation was de-aerated distilled water, having a density of 0.9796 grams per cubic centimeter at 78°F. The viscosity of a sample of this water at 78°F was found to be 0.8920 centipoises.

Reservoir Oil

The oil used to saturate the model prior to each run was Phillips 66, D-168 commercial grade iso-octanes. The density of this oil was found to be 0.6932 grams per cubic centimeter at 78°F while the viscosity at this temperature was 0.4673 centipoises.

Flooding Water

The flooding water used to displace the oil was deaerated distilled water colored with a fluorescent dye, Dupont Uranine "B". Having a density of 0.9798, the flooding water had a viscosity of 0.8922 centipoises.

Interfacial Tension

The interfacial tension between the flooding water and the oil after corrections for ring size and buoyancy effect was found to be 45.86 dynes/cm. at 78°F.

Critical Rate Study

General scaling laws applicable to three-dimensional systems were derived by Rappoport(55). These laws established on a mathematical basis are applicable to incompressible, immiscible, two-phase flow systems. In the derivation of these laws particular consideration was given to the role of the capillary pressure functions. Applying these scaling laws to laboratory investigations, Rappoport, Carpenter and Leas(56) investigated the effect of rate upon waterflood recovery. Their findings showed that at the lower values of injection rate the oil recoveries and flood efficiencies were markedly influenced by the injection rate. However, the effect of rate on flooding performance became less pronounced with increasing rates and eventually, after a sufficiently high injection rate, the influence of rate became negligible. The

rate at which this occurs has since been termed the critical injection rate.

A dimensionless group of parameters, which largely governs the displacement of oil by water in a two-dimensional flow system was derived by the above-mentioned authors. This group designated as the capillary pressure coefficient, defines the relative importance of capillary forces in the displacement of oil by water. The group is defined as follows:

$$C_2 = \frac{q\mu_w}{\sigma_{ow} \cos\theta \sqrt{K\phi}}$$

where q is the injection rate per unit sand thickness, μ_w is the water viscosity, σ_{ow} is the oil-water interfacial tension, K is the permeability and ϕ is the porosity. It was found that for a given value of C_2 all porous media of given geometry operated under similar boundary conditions, having the same mobility ratio and the same j function would yield the same flooding performance. Above a critical value of C_2 the two-dimensional water-oil displacements are independent of rate and classified as being stabilized. To insure the results would be rate independent, a critical rate study was conducted on the model used in this report; the results of this study follow in a later section.

EXPERIMENTAL PROCEDURE

Initially the model was evacuated from the ten wells around the periphery of the model. The vacuum was held for approximately one hour at a value less than 0.5 millimeters of mercury. The model was then saturated with water from the center well of the pattern. The initial interstitial water saturation was established by injecting oil into the center well and producing from the peripheral wells. A record of the amount of water displaced by oil was kept, from which the connate water saturation could be calculated.

De-aerated distilled water, colored with the fluorescent dye, was injected at a constant rate into four wells while the fluid production from the center well was measured. The flood fronts were traced onto the surface of the lucite top with a wax marking pencil at convenient intervals during the run.

After each flood was completed a photograph of the entire flood pattern was taken. The camera was leveled above the model using a fish eye level. A typical flood pattern is illustrated in Figure 6. The area contacted by the injected water was found by enlarging the photograph and using a planimeter to measure the area swept out.

After each run, the model was cleaned using a vacuum pump connected to the center well while clean water lines were connected to the peripheral wells. Once all of the dye was flushed out, the model was completely saturated with water.

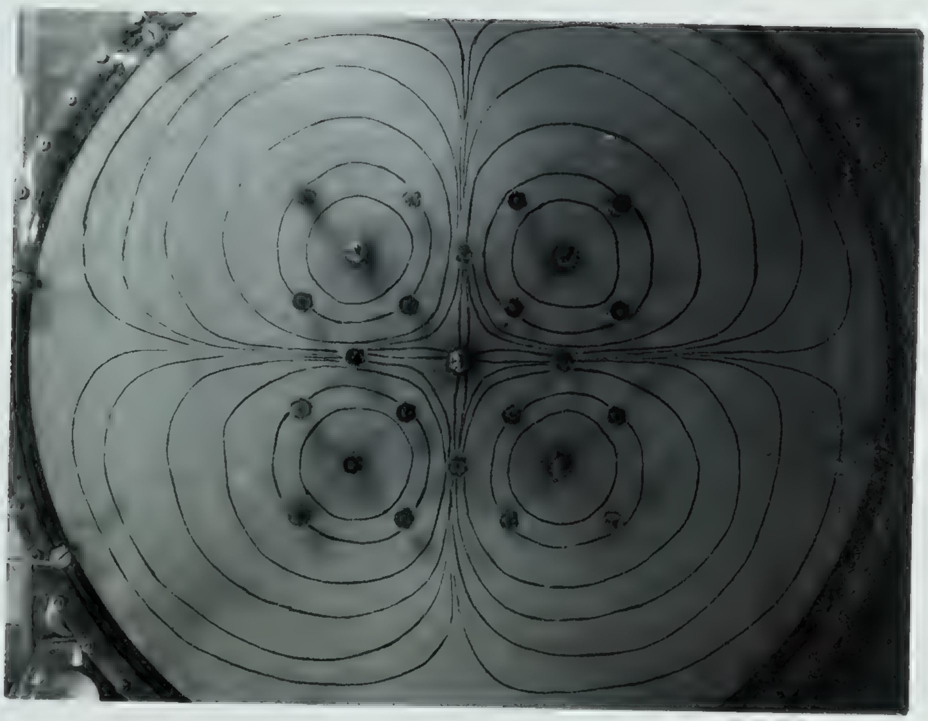


FIGURE 6

PHOTOGRAPH OF A TYPICAL FLOOD SHOWING THE LOCATION
OF THE FLOOD FRONT DURING VARIOUS STAGES OF INJECTION

Oil was then injected into the center well, again keeping record of the amount of water displaced by oil. The model was then ready for the next run.

For each run conducted, a record was kept of the water produced, the oil produced and the producing water-oil ratio. In all cases the floods were terminated after approximately fourteen five-spot pore volumes of water had been injected.

Initially a number of runs was taken to determine the best size of pattern to use. It was desirable to use the largest pattern possible. Several pattern sizes were tried and it was found that interference from the boundary was considerable with the larger sized patterns. A pattern having a distance of eight inches between the corner producers was finally chosen as the pattern to be used.

A series of runs was conducted to determine the critical rate of flooding for the model. Following this a series of runs was taken to evaluate the effect of back pressure on the production performance.

EXPERIMENTAL RESULTS AND DISCUSSION

The experimental data presented have been divided into three groups, depending upon the purpose of the run in question. The first series of runs, Flood series 1, were conducted to determine the best size of pattern. It was desirable from a practical standpoint to use the largest possible pattern. This would facilitate the tracing of the flood patterns on to the model surface as well as reducing the percentage error induced by tracing the flood patterns. In addition, the larger the pattern, the greater the number of observations that could be made before abandonment conditions were reached.

It was found that using the largest pattern the boundary of the model interfered with the flood patterns before the desired cut off point was reached. In order to minimize this effect without introducing the undesirable influences of too small a pattern, a medium sized pattern was chosen as the optimum size. The pattern chosen was one having a side of eight inches between injection wells. All of the runs in this series were conducted with back pressure of 0.0151 psig and a rate of 400 cc/hr per injection well. The results of a typical run in this series are presented in Tables 8 and 9 of the Appendix.

The second series of runs conducted were a series of runs used to determine the critical rate of flooding as discussed in an earlier section. These runs prefixed with a 2

were on the 8-inch pattern and were again conducted with a back pressure of 0.0151 psig. The results of these runs are tabulated in Tables 11 to 17 inclusive and can be found in the Appendix.

The third series of runs were conducted to determine the effect of back pressure on the performance of a normal five-spot. The results of these runs, numbered with a prefix 3,are presented in Tables 18 to 33 inclusive and can also be found in the Appendix.

Of prime importance in any flooding operations is the amount of oil recovered. The amount of oil recovered depends upon several factors. Of primary importance is the amount of oil in place. Of secondary importance, of the oil in place, how much can be recovered? The amount of oil which can be recovered in turn is dependent upon the volume of the reservoir contacted as well as the displacement efficiency. In a constant thickness reservoir such as the one under consideration, the volume of the reservoir contacted is directly dependent upon the areal sweep efficiency. The displacement efficiency of a water flood is the amount of oil recovered from any contacted section expressed as a fraction of the amount of hydrocarbon pore volume with this section. In flooding a porous medium, the amount of oil which can be recovered from that portion of the media contacted by the displacing fluid is dependent upon the residual oil saturation.

The residual oil saturation is the fraction of oil left behind regardless of the amount of displacing fluid that passes through the medium. In the case of the model under consideration the combination of a highly favorable mobility ratio with a water wet system produces a displacement efficiency very close to 100%. Hence, for all intensive purposes in this study, the displacement efficiency was considered to be 100%. The amount of oil recovered thus depends directly on the area contacted. Areal sweep efficiency is defined as the measure of the area of the reservoir which is contacted by the displacing fluid at any time compared to the unit area of the pattern.

In addition to the above factors, there is an economic factor in water flooding which must also be considered. From a practical stand point it becomes undesirable to continue to produce a field or a well once the water-oil ratio becomes too high. The cost of lifting and disposing of the produced water is a governing factor on the life of a well. Thus, it is desirable to know the water-oil ratio at the various times throughout a flooding operation.

From the above discussion, it may be seen that the important factors are the amount of oil recovered, the area swept out, and the producing water-oil ratio. For each of the runs taken the oil recovered as a percentage of oil in place was plotted against the total throughput of the model. The throughput of the model is defined as the total amount of

fluid produced. Since the oil in place is not a constant, it was desirable to also plot the oil recovered in five-spot hydrocarbon pore volumes against throughput. The water-oil ratio and area swept divided by the unit area were also plotted for each of the runs.

For the purpose of determining the critical rate of flooding for the model, an analysis was made of the percentage recovery and area swept against the scaling coefficient, C_2. All of the terms in the scaling coefficient are constant except the injection rate, therefore, a change in the coefficient represents only a change in rate. Figure 7 represents the change in the percentage of oil recovered as a function of the rate while Figure 8 represents the change in areal sweep efficiency with injection rate. The parameter in both these cases being the cumulative pore volumes of water injected.

Rappoport(56) has shown that the oil recovery should decrease with increasing rate up to a critical rate at which point further increases in rate do not significantly affect the oil recovered. Figure 7 shows that all of the rates employed must be above the critical rate since the curve shows no influence of rate on the oil recovery. Comparing a study made on a similar model by Culham(20), the critical rate was found to be at a value of the scaling coefficient of 5.5×10^{-3}. The lowest value of scaling coefficient employed in this study is twice this amount. This supports the fact that all of the rates used were stable rates. Figure 8 shows that

FIG 7 FIVE-SPOT WATERFLOOD: RELATIONSHIP BETWEEN OIL RECOVERED AND SCALING COEFFICIENT

PARAMETER (W_{PV})-PORE VOLUMES OF WATER INJECTED

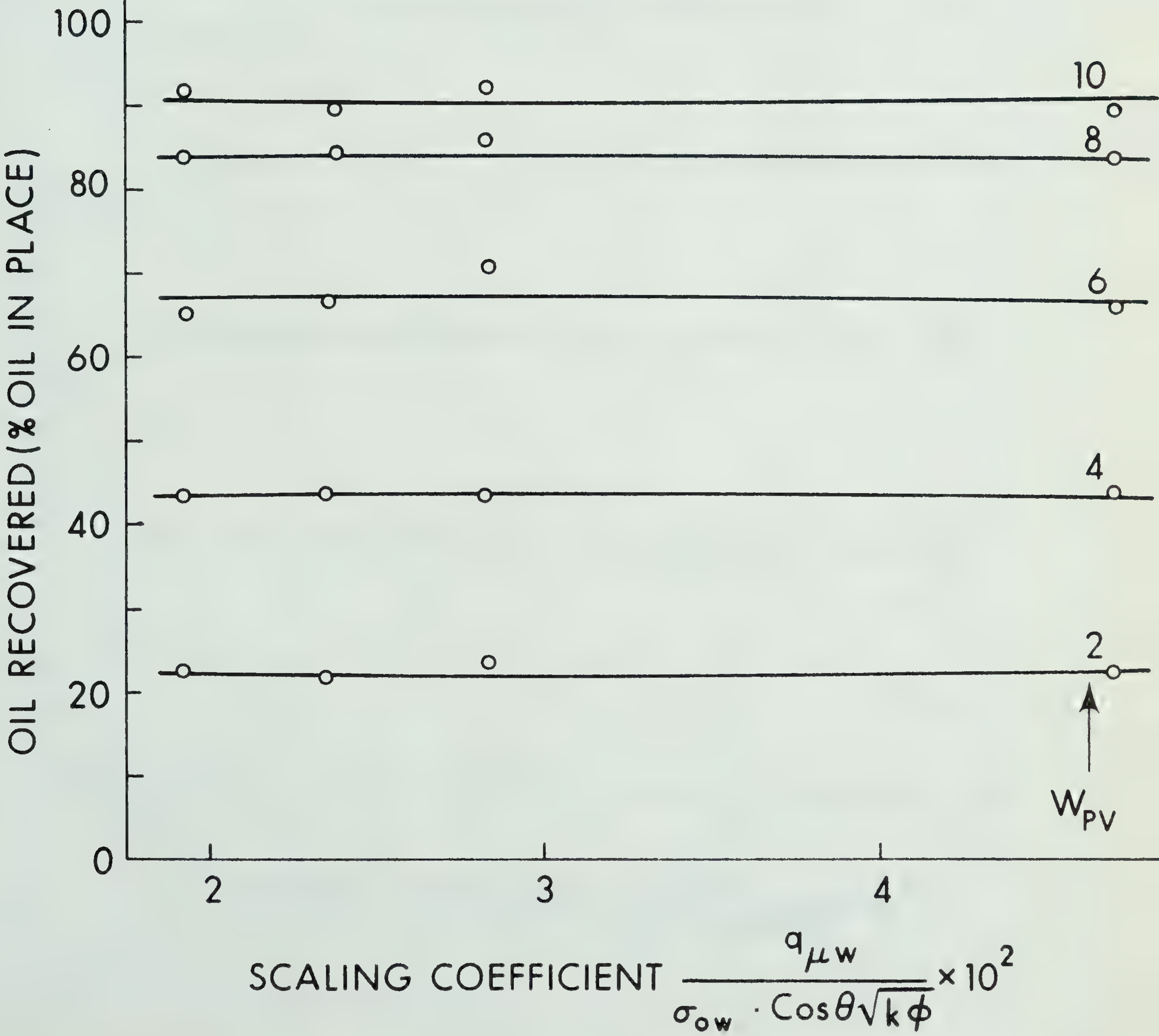
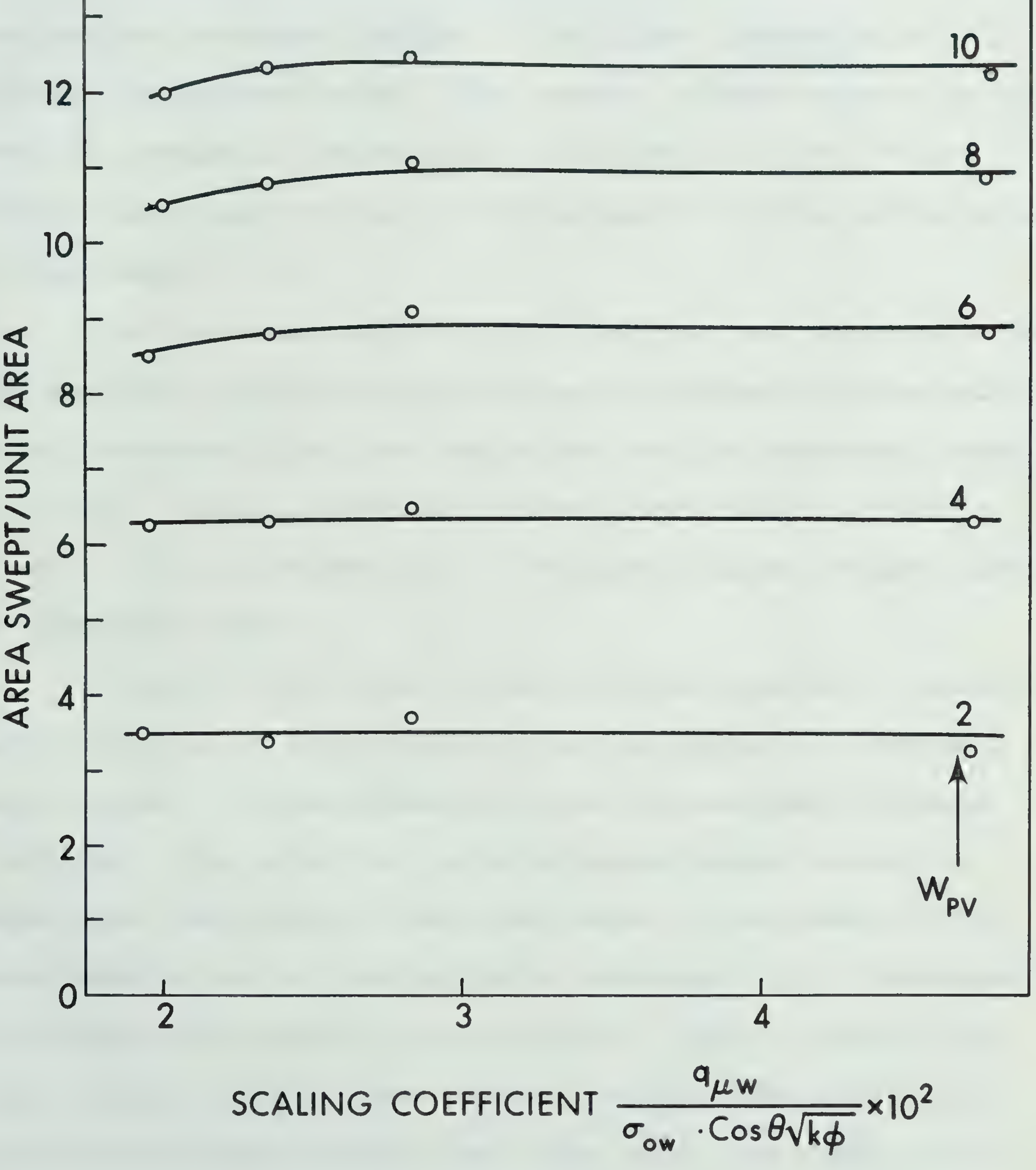


FIG 8 FIVE-SPOT WATERFLOOD: EFFECT OF RATE ON AREAL SWEEP EFFICIENCY

PARAMETER (W_{PV})-PORE VOLUMES ON WATER INJECTED



the rates used did not appreciably alter the areal sweep efficiencies at various stages of cumulative throughput. This also supports the theory that all of the rates were above the critical rate.

The general shape of each of the curves plotted for the various runs was similar. A detailed discussion of a typical run follows below. The results of the balance of the runs are presented graphically in Figures 12 to 27. These figures have been grouped in the Appendix for the convenience of the reader.

Earlier discussion in this section has indicated that the important factors which must be considered are the amount of oil recovered, the area swept out and the producing water-oil ratio. These results are shown graphically in Figures 9, 10 and 11 for run number 1-A. The significance of each curve is discussed below.

Figure 9 is a plot of the oil recovered as a percentage of the oil in place against the throughput in five-spot pore volumes. It was found that the oil recovery followed a straight line up to the point of water break-through at which time the slope of the curve began to decrease and the curve leveled out as the producing water-oil ratio increased. Two factors contribute to this effect. First, some of the water being injected flows directly between the injection well and the producing well and thus, does not sweep out any additional area not already contacted. Since no oil remains

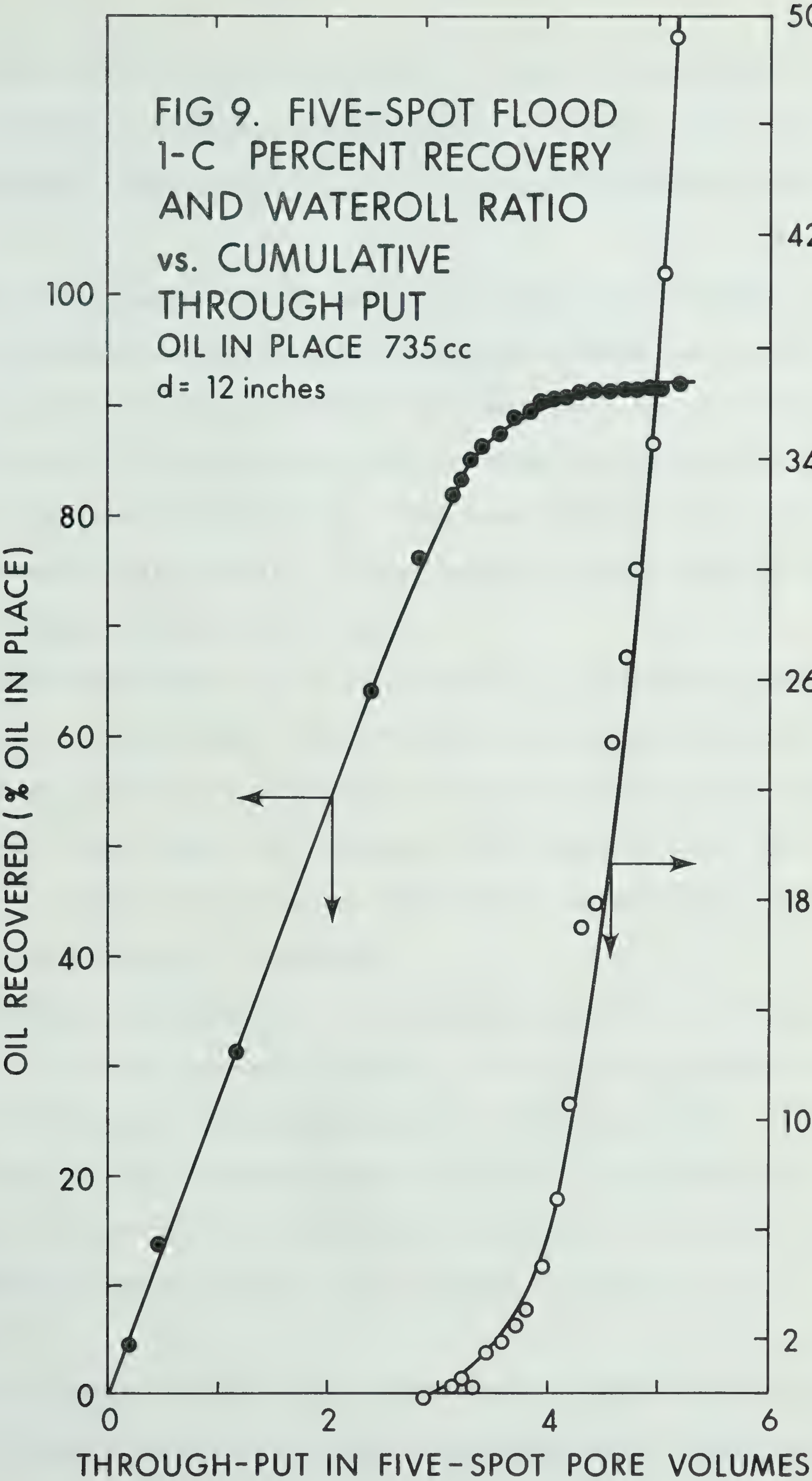


FIG 9. FIVE-SPOT FLOOD
1-C PERCENT RECOVERY
AND WATEROLL RATIO
vs. CUMULATIVE
THROUGH PUT
OIL IN PLACE 735 cc
d= 12 inches
OIL RECOVERED (% OIL IN PLACE)
INSTANTANEOUS WATER OIL RATIO
THROUGH-PUT IN FIVE-SPOT PORE VOLUMES
0
20
40
60
80
100
2
4
6
10
18
26
34
42
50

in this area this portion of the water does not contribute to the oil recovery. Second, as the amount of water being produced increases, the amount of oil which can be produced decreases.

The area swept out by the displacing fluid, water, was found to be radial in the initial flooding stages as the effect of the sink at the producing well was felt by the flood front, it began to distort and pull towards the producing well on the sides facing these wells. The back side of the flood remained essentially radial. A photograph of the typical flood patterns traced is shown in Figure 6.

The second curve shown on Figure 10 is the water-oil ratio curve. In all cases the water-oil ratio increased slowly during the first pore volumes of throughput following water breakthrough, then began to increase very rapidly such that the water-oil ratio curve plots with almost a vertical slope in the latter stages of injection.

Because the amount of oil in place initially influences the amount of oil recovered, another plot of oil recovered expressed in five-spot hydrocarbon pore volumes was made. The general shape of this curve,shown in Figure 10,was found to be similar to that of the percentage recovery curve but takes into consideration the effect of a change in initial oil saturation.

The plot of areal sweep efficiencies versus cumulative throughput show that the area swept increases at a decreasing

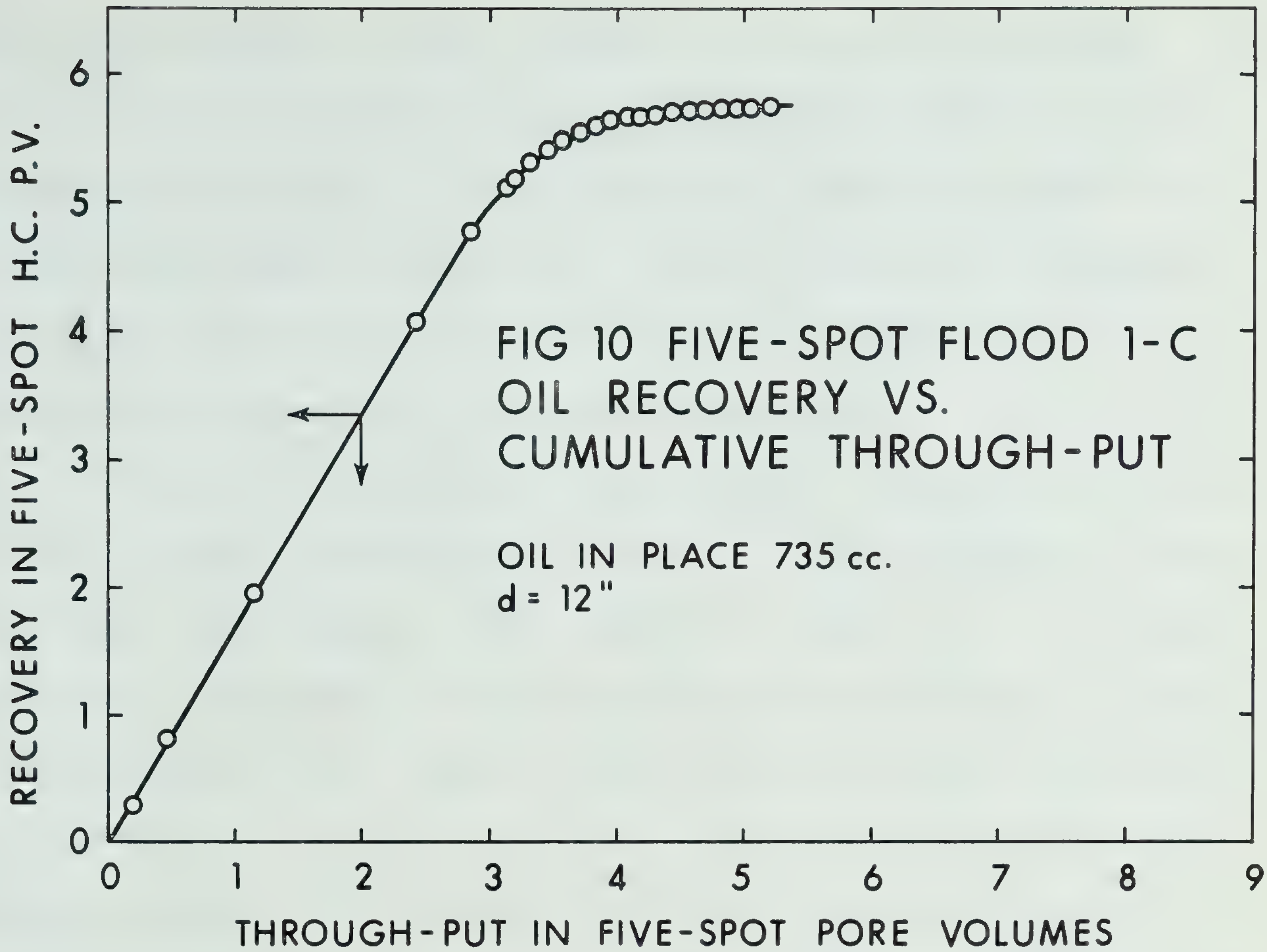


FIG 10 FIVE-SPOT FLOOD 1-C
OIL RECOVERY VS.
CUMULATIVE THROUGH-PUT

OIL IN PLACE 735 cc.
d = 12"

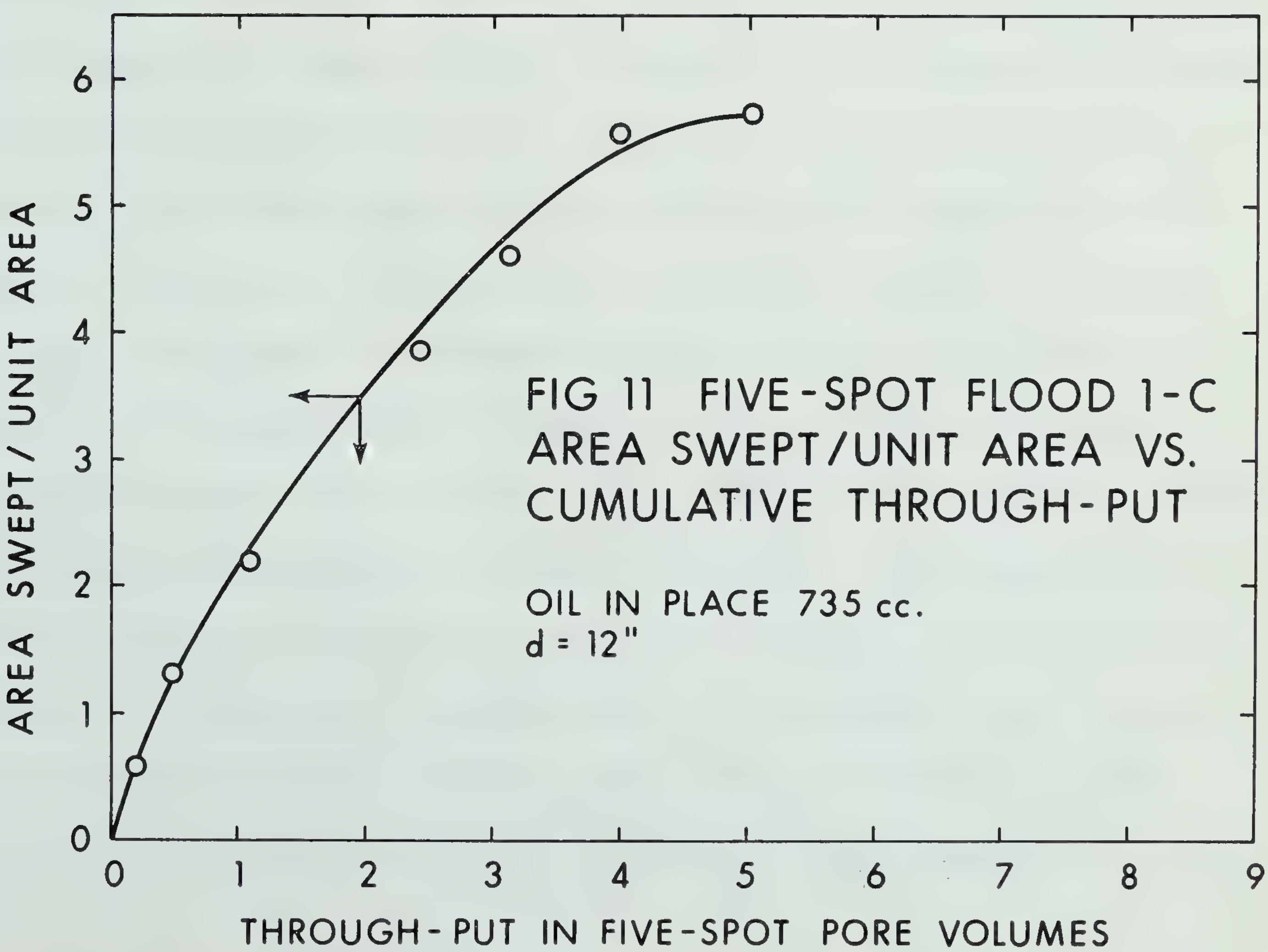


FIG 11 FIVE-SPOT FLOOD 1-C
AREA SWEPT/UNIT AREA VS.
CUMULATIVE THROUGH-PUT

OIL IN PLACE 735 cc.
d = 12"

rate as the number of pore volumes of injection increases. The curve levels off at the higher water-oil ratio until it is nearly horizontal, at this point the additional area being contacted was almost negligible. Thus, additional injection would result in very little additional oil production. At this point the water-oil ratio was very high.

The area contacted by the time the cumulative throughput was 10 pore volumes varied from 10 times the pattern area to 13 times the pattern area, depending upon the back pressure imposed on the system. These relatively high values of areal sweep efficiency are a direct result of the highly favorable mobility ratio. Due to the lack of published literature on isolated systems, it was very difficult to obtain data for comparison purposes. However, Culham, using a similar system on an isolated 9 spot pattern, found an areal sweep efficiency of 8 times the pattern area. Comparing the two patterns in question one would expect to get much higher sweep-outs with a normal five-spot than with the nine-spot pattern. Hence, his results support the high values of sweep efficiency obtained. As pointed out in the literature survey, adapting the results of Caudle,Erickson and Slobod to the pattern which most closely resembles a normal five-spot, the areal sweep efficiencies obtained for a mobility ratio of 1/3 are of the order of 10 times the pattern area. In general, one can say on the basis of these results that the contribution of the area outside the normal well pattern is very significant at

this low mobility ratio.

Two of the runs, one from series two and one from series three, were conducted with the same condition imposed upon the model. By comparing the results of the two runs an indication of the reproducibility of the results can be obtained.

The production histories of the two runs are plotted for comparison on Figure 28. Since the number of data points for each run was large, only every second value was used for this plot. Because of the close agreement between the two runs, if all of the points are used the points cluster one on top of another, and it was difficult to see individual points. The Figure shows that within the limitation of experimental error, the performance of run 3-B duplicates the performance of run 2-C. Figure 29, which is a plot of the areal sweep efficiency data for the two runs, also shows a close agreement between the two runs. This close agreement between the runs indicates that the model results are reproducible. A second conclusion which can be drawn from these figures is that the model properties are not altered significantly from one run to the next by repetitively flooding the model without changing the pack.

The results of the series 3 runs can be compared to determine the effect of a change in back pressure on the performance of the pattern flood. The series consisted of 8 runs with the back pressure varying from 0 psig to 0.116 psig.

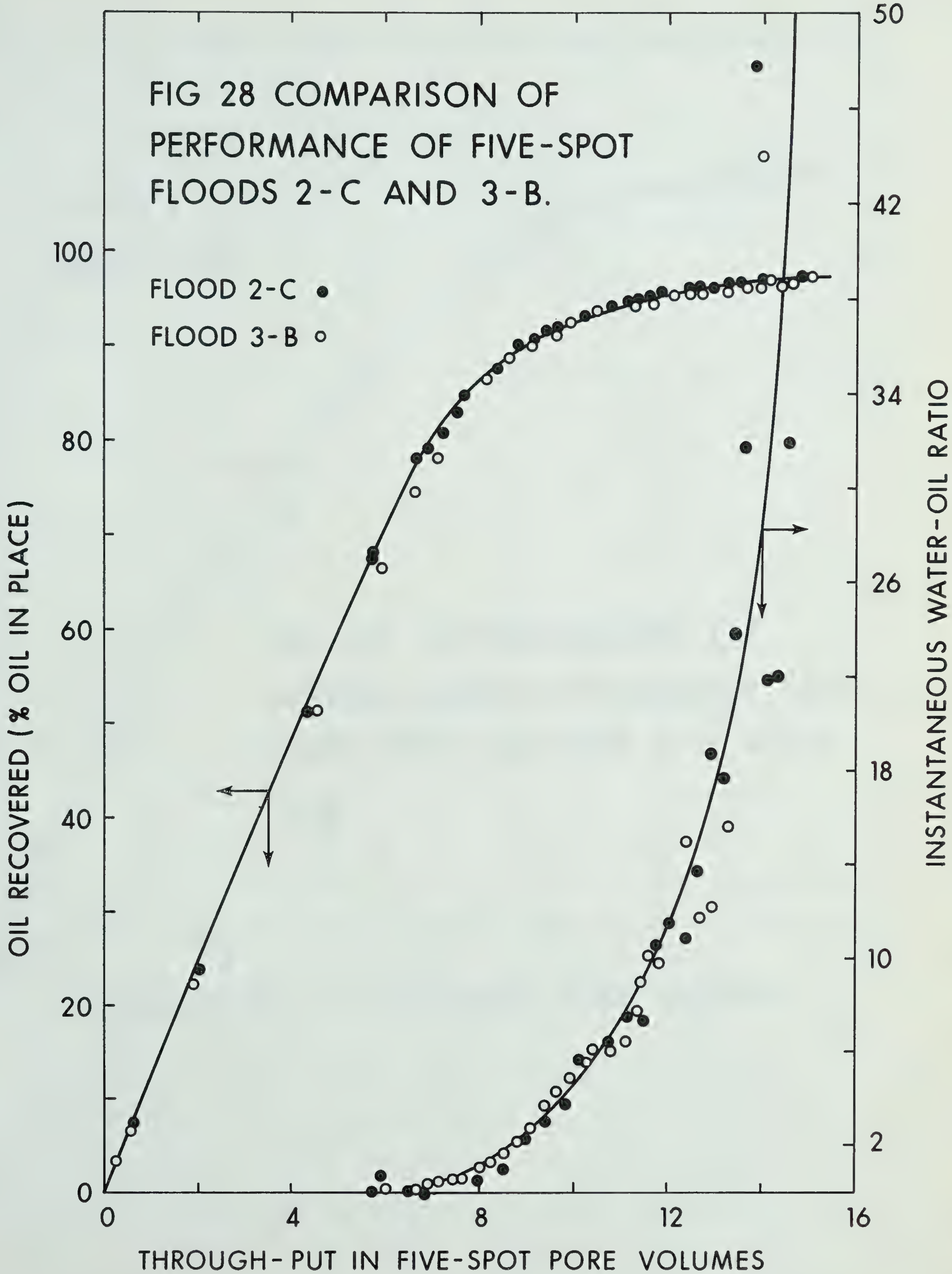


FIG 28 COMPARISON OF PERFORMANCE OF FIVE-SPOT FLOODS 2-C AND 3-B.

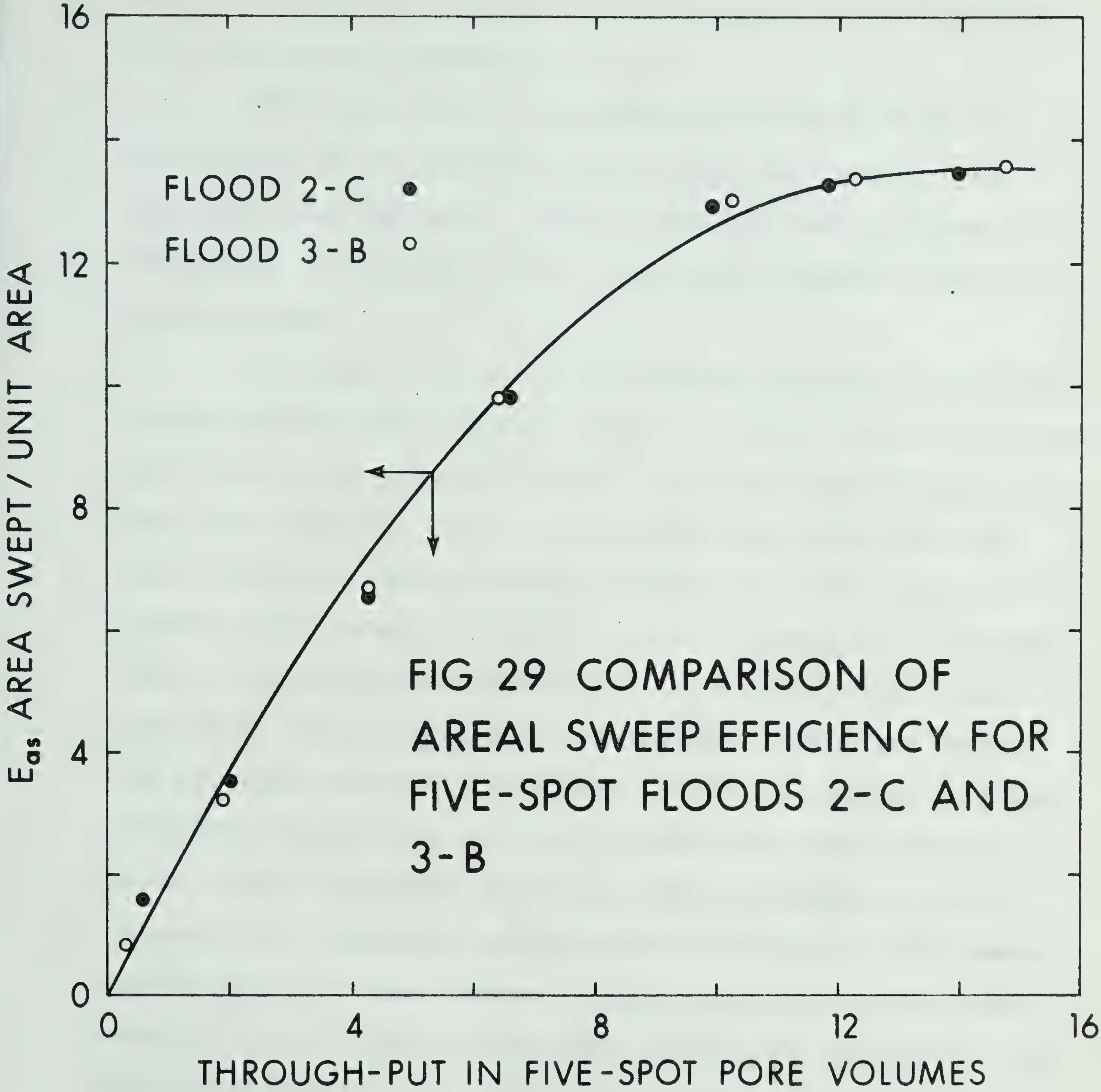


FIG 29 COMPARISON OF AREAL SWEEP EFFICIENCY FOR FIVE-SPOT FLOODS 2-C AND 3-B

Two of the series 3 runs are not considered in the discussion for the following reasons:

Run number 3-G is not considered because a partial plug off of the production well occurred during this run. Since the plug off would induce additional back pressure on the system, an accurate value of the back pressure could not be determined.

Run number 3-D is not considered because of the unusual results demonstrated during this run. The initial oil in place for this run was unusually high. The recoveries obtained in turn were unusually high. It was suspected that a partial plug off of the production well during the establishment of connate water caused the amount of oil in place to be greater than it normally would have been. Oil was injected in the peripheral wells during the establishment of connate water and produced from the center well. Since the center well was partially plugged off, the oil injected into the peripheral wells caused a pressure build-up inside the model,in effect expanding the reservoir at the same time causing the pressure in the model to rise. Hence, at the beginning of the flood, the model would have an artificial reservoir pressure not present in the other runs. This pressure alone, without the aid of the injected water was sufficient to cause production. Hence, as the water was injected into the reservoir, oil was being produced at a much faster rate. Water breakthrough for this run occurred much later than for the other runs, however,

once the water broke through, the water-oil ratio climbed very rapidly and the oil production after breakthrough was negligible.

The series 3 runs were plotted for comparison in Figures 30, 31 and 32. Figure 30 is a plot of the areal sweep efficiencies measured for the series 3 runs. Up until about 4 pore volumes of injection, the area swept out is unaffected by the back pressure. However, the effect of back pressure increases as the throughput increases until after 12 pore volumes of injection the area swept out changes from approximately 10 times the pattern area at a back pressure of 0.116 psig to nearly 14 times the pattern area at a back pressure of 0 psig.

The effect of a back pressure change on the amount of oil recovered is shown in Figure 31, which is a plot of the oil recovery in five spot hydrocarbon pore volumes as a function of cumulative throughput with back pressure as a parameter. The linear portion of the oil recovery curve is unaffected by a change in back pressure, however, the non-linear portion of the curve is altered by changing the back pressure. Figure 32 is an enlargement of the non-linear portion of Figure 31.

To better illustrate the effect of back pressure on the performance of the flood, cross plots of the data were made. Figure 33, which is a cross plot of Figure 30, shows how the area swept out is affected by the back pressure on

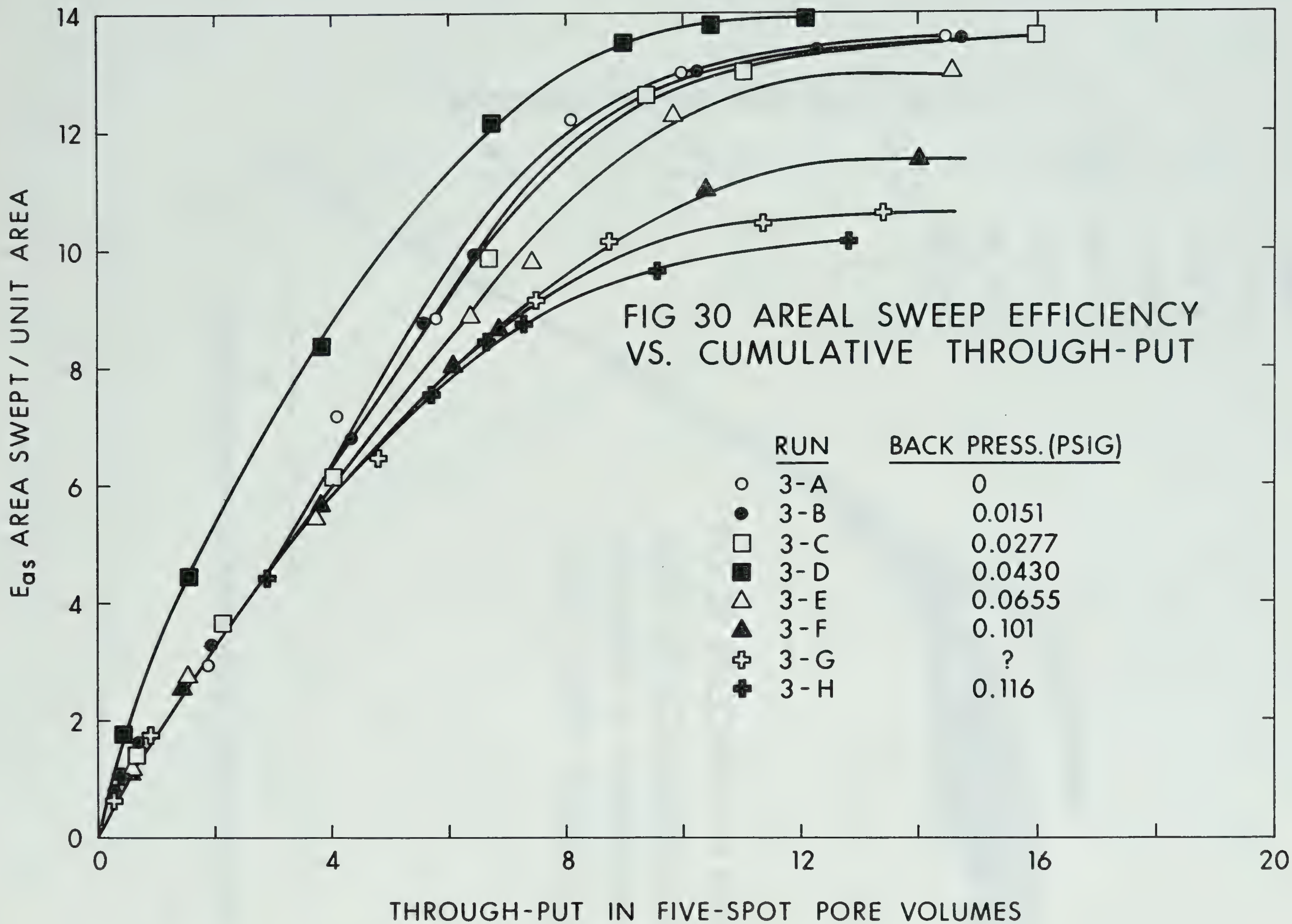


FIG 30 AREAL SWEEP EFFICIENCY
VS. CUMULATIVE THROUGH-PUT
RUN
BACK PRESS. (PSIG)
3-A 0
3-B 0.0151
3-C 0.0277
3-D 0.0430
3-E 0.0655
3-F 0.101
3-G ?
3-H 0.116
E_{as} AREA SWEPT / UNIT AREA
THROUGH-PUT IN FIVE-SPOT PORE VOLUMES
0
2
4
6
8
10
12
14
0
4
8
12
16
20

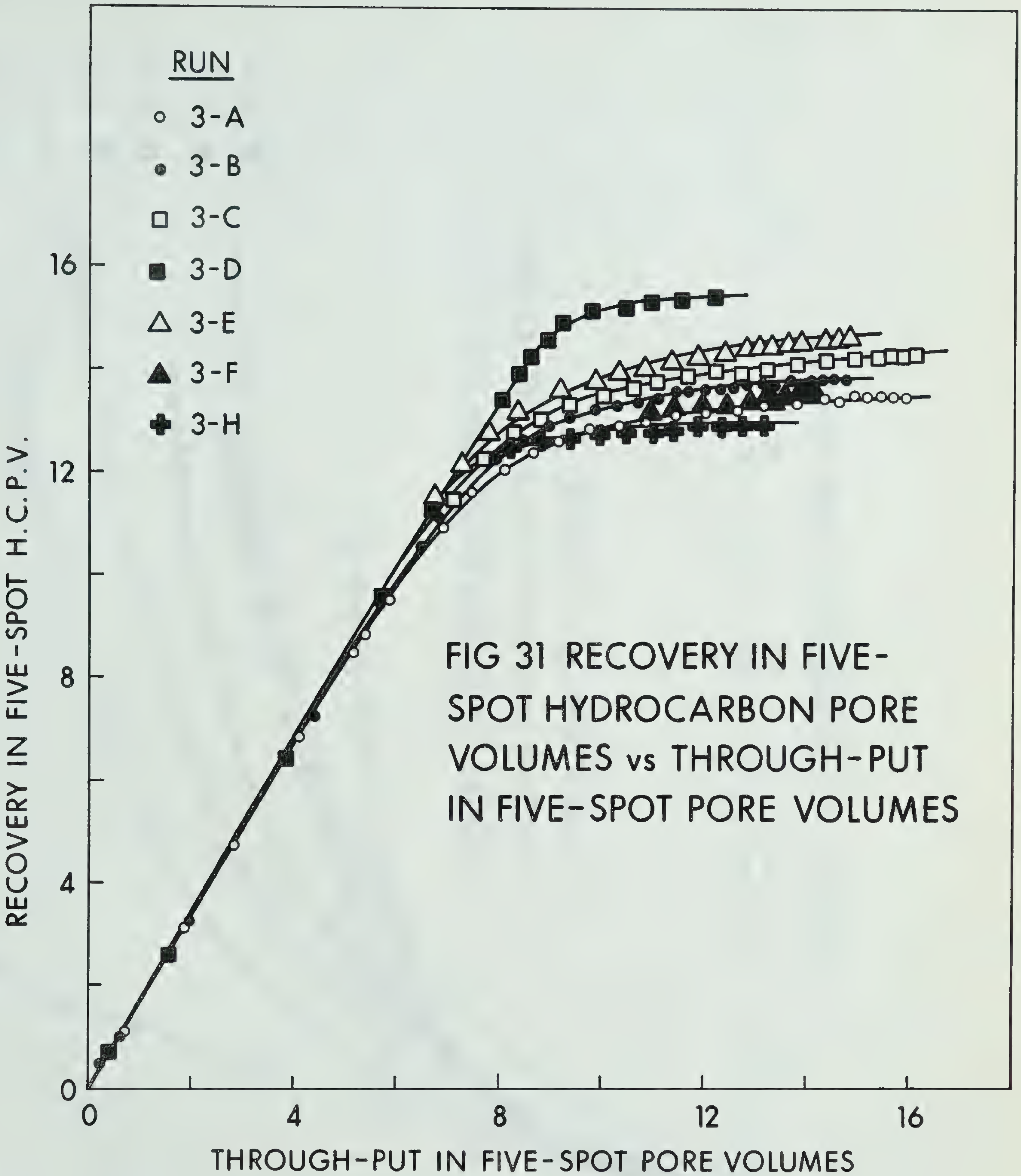


FIG 31 RECOVERY IN FIVE-SPOT HYDROCARBON PORE VOLUMES vs THROUGH-PUT IN FIVE-SPOT PORE VOLUMES

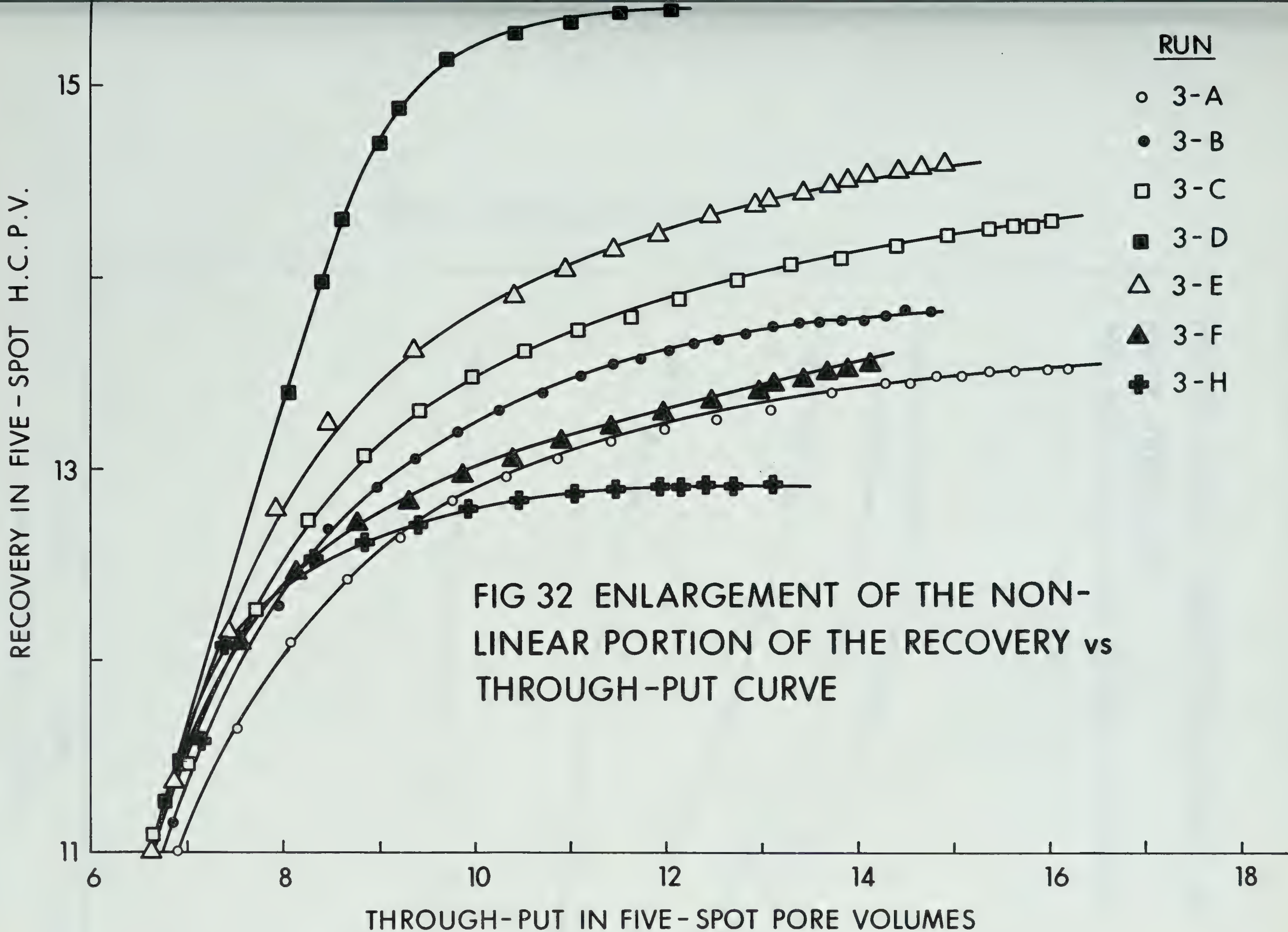


FIG 32 ENLARGEMENT OF THE NON-LINEAR PORTION OF THE RECOVERY vs THROUGH-PUT CURVE

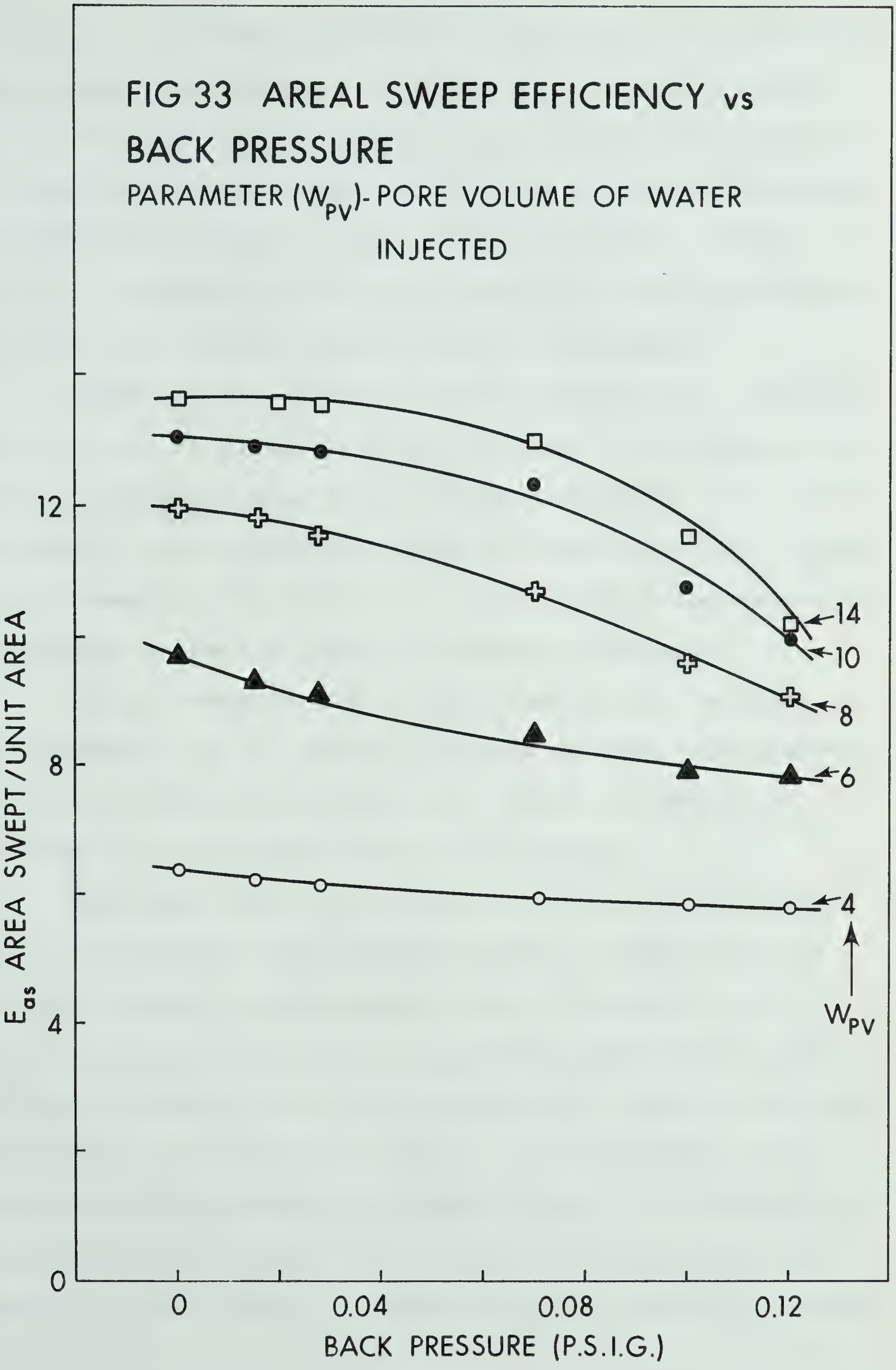


FIG 33 AREAL SWEEP EFFICIENCY vs
BACK PRESSURE
PARAMETER (W_{PV})- PORE VOLUME OF WATER
INJECTED
E_{as} AREA SWEPT/UNIT AREA
0
4
8
12
0
0.04
0.08
0.12
BACK PRESSURE (P.S.I.G.)
14
10
8
6
4
W_{PV}

the system. The degree to which the sweep-out is influenced depends upon the position of the flood. Figure 30 showed that up to 4 pore volumes of injection a change in back pressure had little or no effect. At 4 pore volumes of injection the effect of a change in back pressure is small, however, Figure 33, shows that as the cumulative throughput increases the effect of a change in back pressure increases.

Figure 34 is a plot of the oil recovery as a percentage of the oil in place at various amounts of throughput versus back pressure. This figure reflects directly the effect the change in back pressure has on the area swept out. Since the area swept out is less as the back pressure increases,the oil recovery is less as the back pressure increases.

The oil recovered as a percentage of oil in place at a throughput of 14, changes from 96% at zero back pressure to 69% at a back pressure of 0.116. Again the effect is less severe at the lower values of throughput.

The cross plot of recovery in five-spot hydrocarbon pore volumes versus back pressure, Figure 35 shows the oil recovery expressed in this manner first increases as the back pressure increases up to a value of approximately 0.05 psig then decreases as the back pressure is further increased. On the basis of the previous plots, one would expect this curve to be a continuously decreasing curve. No explanation for the behavior of this curve at the low back pressure can be offered, other than it is believed to be caused by changes

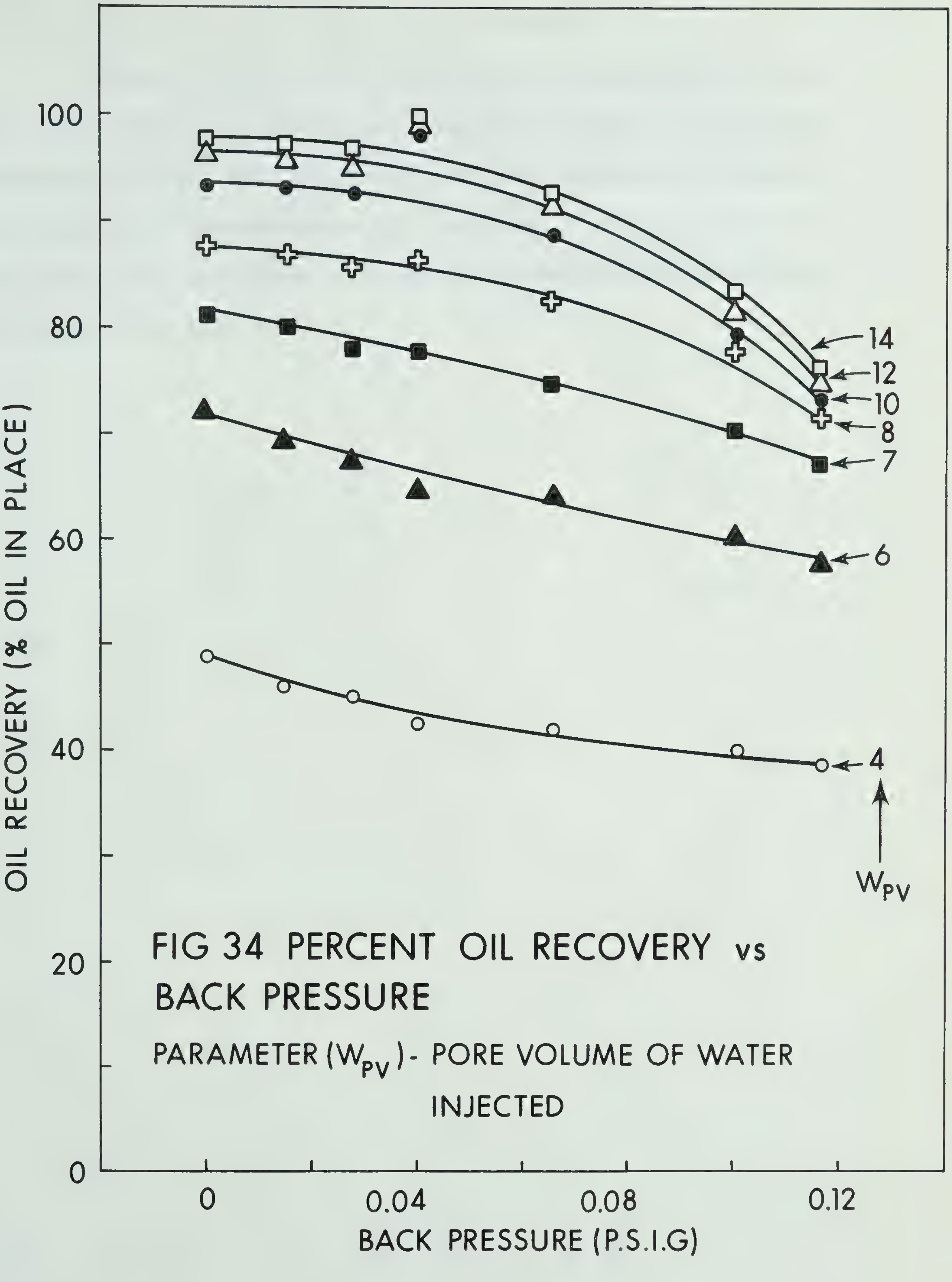


FIG 34 PERCENT OIL RECOVERY vs BACK PRESSURE

PARAMETER (W_{PV}) - PORE VOLUME OF WATER INJECTED

in the initial oil saturation of the model.

Figures 33, 34 and a portion of 35 show that as the back pressure on the flood pattern is increased, the area contacted is less and the amount of oil recovered is less. The second is a consequence of the first. It is also possible that the influence of back pressure may be attributed to a well bore area effect.

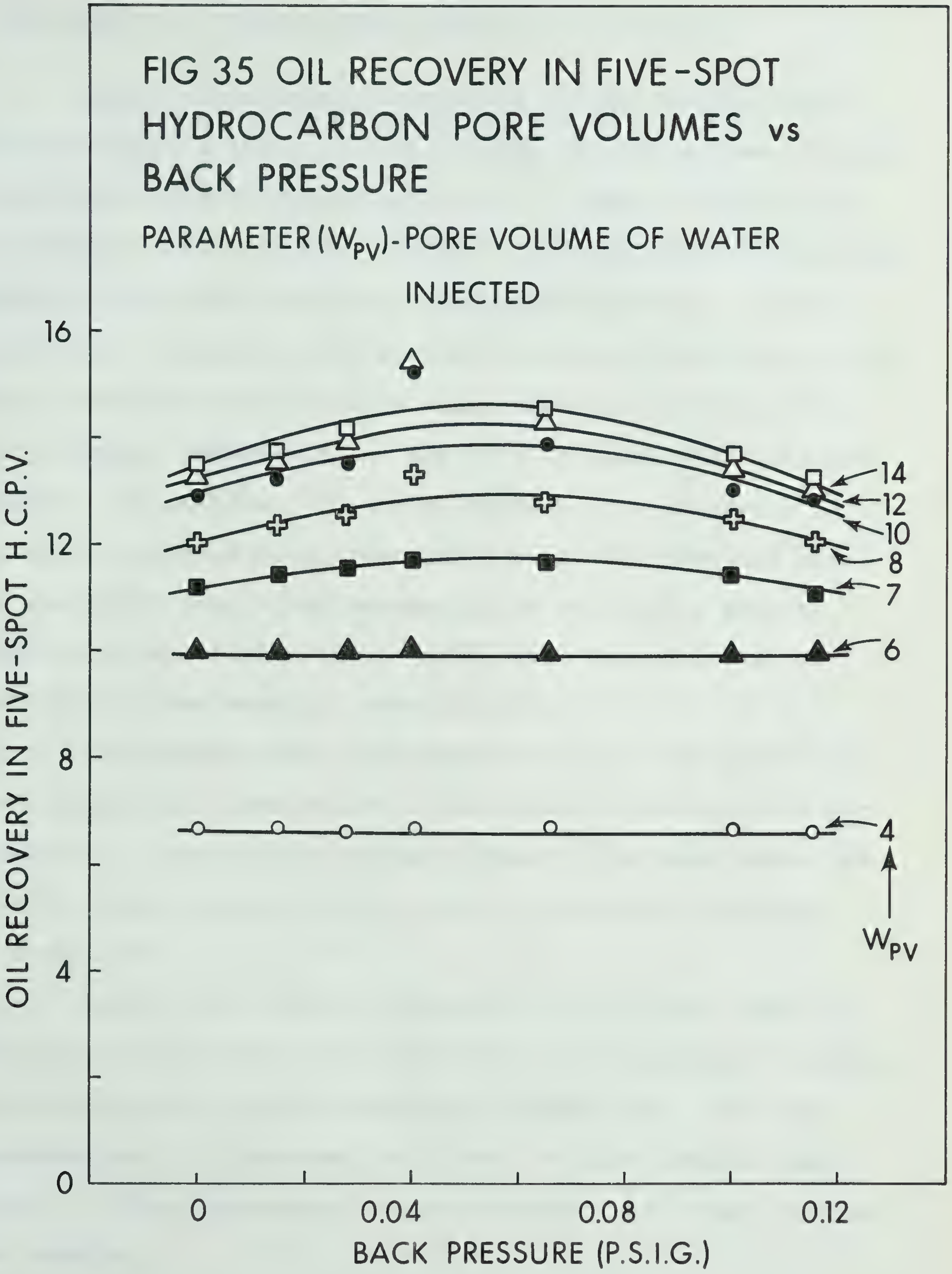


FIG 35 OIL RECOVERY IN FIVE-SPOT
HYDROCARBON PORE VOLUMES vs
BACK PRESSURE
PARAMETER (W_{PV})-PORE VOLUME OF WATER
INJECTED
OIL RECOVERY IN FIVE-SPOT H.C.P.V.
BACK PRESSURE (P.S.I.G.)
0
4
8
12
16
0
0.04
0.08
0.12
14
12
10
8
7
6
4
W_{PV}

PRACTICAL APPLICATION AND LIMITATION OF THE MODEL

One of the severe limitations of the data obtained in this study is that it is applicable only to systems having a mobility ratio of approximately 1/3. There is sufficient evidence in the literature showing that mobility ratio changes greatly affect the production performance of water flood operations. Secondly, the results obtained in this model are for an entirely liquid filled reservoir which corresponds to the situation achieved after gas fill up under practical conditions. In addition, the model represents a reservoir of constant thickness with impermeable barriers above and below the producing zone. The assumption of negligible gravity effects has the further implication that the reservoir be thin or have low vertical permeability.

The porous media represented by a uniform glass bead pack imposes the limitations of homogeneous porosity and permeability. A marked difference between glass bead packs and natural porous systems is the bulk of the pores are nearly of equal size.

Lastly, the system represented is a closed system in which the boundaries of the reservoir are impermeable barriers so that no fluid can be transferred across them. The data presented only illustrates the effect of back pressure and volume of fluid throughput on performance. All other factors are constant.

CONCLUSIONS

The results of this study led to the following conclusions.

1) Since changing the rate did not influence the performance of the pattern studied, it is the conclusion that all of the rates were above the critical rate.

2) Since the rates are above the critical rate, the capillary pressure effects did not alter the results obtained.

3) Because of the close agreement between runs 3-B and 2-C, the results are reproducible.

4) The model properties are not changed by repetitive flooding of the model.

5) The area contacted by the flood pattern is considerably greater than the pattern area when the flood is continued to high water-oil ratios.

6) The area contacted by the displacing fluid is sharply reduced as the back pressure on the system is increased.

7) In pilot water flood operations, a considerable amount of the production could come from the area beyond the well pattern, hence, a single isolated pilot pattern may not give accurate estimates of the expected performance of a fully developed flood.

RECOMMENDATIONS

1) In constructing glass bead models one should use a range of size of glass beads in order to more closely represent a natural porous system.

2) In order to obtain a maximum density pack, the model should be vibrated for a long period of time.

3) A higher viscosity fluid should be used as the reservoir oil in order to obtain a higher, less favorable mobility ratio.

4) A more accurate means of measuring the area swept out should be adopted. A continuous record of the flood patterns would be advantageous. This could be achieved with either X-ray shadowgraph techniques or a movie camera.

5) Larger models should be employed so that the boundaries of the model could be farther away from the pattern area, thus reducing boundary effects.

BIBLIOGRAPHY

1. Amyx, J.W., Bass, D.M., Jr., and Whiting, R.L.: "Petroleum Reservoir Engineering", McGraw-Hill Book Co. Inc. (1960).

2. Aronosky, J.S.: "Mobility Ratio - Its Influence in Flood Patterns During Water Encroachment", Trans.AIME (1952), 195, 15.

3. Aronosky, J.S. and Ramey, H.J., Jr.: "Mobility Ratio - Its Influence on Injection or Production Histories in Five-Spot Water Floods", Trans. AIME (1956),207, 205.

4. "A.S.T.M. Standards on Petroleum Lubricants", American Society for Testing Materials, (1958).

5. Bartell, F.E. and Osterhof, H.S.: "Determination of the Wettability of a Solid by a Liquid", Ind. Eng. Chem. (1927), 19, 1277.

6. Bobek, J.E., Mattax, C.C., Denekas, M.O.: "Reservoir Rock Wettability - Its Significance and Evaluation", Trans. AIME (1958), 213, 155.

7. Botset, H.G.: "The Electrolytic Model and Its Application to the Study of Recovery Problems", Trans. AIME (1946), 165, 15.

8. Bruce, W.A.: "An Electrical Device for Analyzing Oil-Reservoir Behavior", Trans. AIME (1943), 151, 112.

9. Buckley, S.E. and Leverett, M.C.: "Mechanism of Fluid Displacement in Sands", Trans. AIME (1942), 146, 149.

10. Burton, M.E. and Crawford, P.B.: "Application of the Gelatin Model for Studying Mobility Ratio Effects", Trans. AIME (1956), 207, 333.

11. Calhoun, J.C., Jr.: "Fundamentals of Reservoir Engineering", University of Oklahoma Press.

12. Caudle, B.H., Erickson, R.A. and Slobod, R.L.: "The Encroachment of Fluids Beyond the Normal Well Patterns", Trans. AIME (1955), 204, 160.

13. Caudle, B.H. and Witte, M.D.: "Production Potential Changes During Sweep Out in a Five-Spot System", Trans. AIME (1959), 216, 446.

14. Caudle, B.H. and Loncaric, I.G.: "Oil Recovery in Five-Spot Pilot Floods", Trans. AIME (1960), 219, 132.

15. Cheek, R.E. and Menzie, D.E.: "Fluid Mapper Model Studies of Mobility Ratio", Trans. AIME (1955), 204, 278.

16. Craft, B.C., and Hawkins, M.F.: "Applied Petroleum Reservoir Engineering", Prentice-Hall Inc.

17. Craig, F.F., Jr., Geffen, T.M., and Morse, R.A.: "Oil Recovery Performance of Pattern Gas or Water Injection Operations from Model Tests", Trans. AIME (1955), 204, 7.

18. Craig, F.F., Jr., Sanderlin, J.L., Moore, D.W., and Geffen, T.M.: "A Laboratory Study of Gravity Segregation in Frontal Drives", Trans. AIME (1957), 210, 275.

19. Craig, F.F., Jr.: "A Laboratory Model Study of Single Five-Spot and Single Injection Well Pilot Water Flooding".

20. Culham, W.E.: "A Model Study of an Isolated Nine-Spot", unpublished manuscript, M.Sc. Thesis, University of Alberta, (1962).

21. Dalton, R.L., Jr., Rappoport, L.A., Carpenter, C.W., Jr.: "Laboratory Studies of Pilot Water Floods", Trans. AIME (1960), 219, 24.

22. Deppe, J.C.: "Injection Rates - The Effect of Mobility Ratio, Area Swept and Pattern", SPE Journ. June 1961.

23. Dyes, A.B., Caudle, B.H., and Erickson, R.A.: "Oil Production After Breakthrough as Influenced by Mobility Ratio", Trans. AIME (1954), 201, 81.

24. Dykstra, H., and Parsons, R.L.: "Relaxation Methods Applied to Oil Field Research", Trans. AIME (1951), 192, 227.

25. Fay, C.H. and Prats, M.: "The Application of Numerical Methods to Cycling and Flooding Problems", Proc. Third World Petroleum Congress, The Haque (1951), Sect. II, 555.

26. Fischer-Rosenbaum, M.J., and Matthews, C.S.: "Studies on Pilot Water Flooding", Trans. AIME (1959), 216, 316.

27. Gaucher, D.H. and Lindley, D.C.: "Waterflood Performance in a Stratified, Five-Spot Reservoir - A Scaled Model Study", Trans. AIME (1960), 219, 208.

28. Geertsma, J., Croes, G.A., and Schwarz, N.: "Theory of Dimensionally Scaled Models of Petroleum Reservoirs", Trans. AIME (1956), 207, 118.

29. Habermann, B.: "The Efficiency of Miscible Displacement as a Function of Mobility Ratio", Trans. AIME (1960), 219, 264.

30. Hauber, W.C.: "Prediction of Waterflood Performance for Arbitrary Well Patterns and Mobility Ratio", J.P.T. Jan. 1964.

31. Higgins, R.V., Boley, D.W., Leighton, A.J.: "Aid to Forecasting the Performance of Water Floods", J.P.T. Sept. 1964.

32. Hurst, W. and McCarty, G.M.: "The Application of Electrical Models to the Study of Recycling Operations in Gas Distillate Fields", Drilling and Production Practice API (1941), 228.

33. Hurst, W.:"Determination of Performance Curve in Five-Spot Water Flood", The Petroleum Engineer, April 1953.

34. Lee, B.D.: "Potentiometric Model Studies of Fluid Flow in Petroleum Reservoirs", Trans. AIME (1948), 174, 41.

35. "Letter Symbols for Petroleum Engineering and Electric Logging", J.P.T., Oct. (1956), 1.

36. Leverett, M.C., Lewis, W.B., and True, M.E., "Dimensional Model Studies of Oilfield Behavior", Trans. AIME (1942), 146, 175.

37. Marshall, D.L. and Oliver, L.R.: "Some Uses and Limitations of Model Studies in Cycling", Trans. AIME (1948), 174, 67.

38. Matthews, C.S., and Lefkovits, H.C.: "Studies on Pressure Distribution in Bounded Reservoirs at Steady State", Trans. AIME (1955), 204, 182.

39. Matthews, C.S. and Fischer, M.J.: "Effect of Dip on Five Spot Sweep Pattern", Trans. AIME (1956), 207, 111.

40. Muskat, M.: "Two Fluid Systems in Porous Media Encroachment of Water into an Oil Sand", Physics (1934), 5, 250.

41. Muskat, M.: "A Note on a Problem in Potential Theory", Journal of App. Physics (1937), 8, 434.

42. Muskat, M.: "The Theory of Potentiometric Models", Trans. AIME (1949), 179, 216.

43. Muskat, M.: "Physical Principles of Oil Production", McGraw-Hill Book Co. Inc., (1949).

44. Muskat, M.: "Flow of Homogeneous Fluids in Porous Media", McGraw-Hill Book Co. Inc., (1937).

45. Muskat, M.: "The Effect of Permeability Stratification in Complete Water Drive Systems", Trans. AIME (1950), 189, 349.

46. Neilson, I.D.R.: "The Effect of a Free Gas Saturation on the Sweep Efficiency of Isolated Five-Spot", unpublished manuscript, M.Sc. Thesis, University of Alberta (1959).

47. Nobles, M.A. and Janzen, H.B.: "Application of a Resistance Network for Studying Mobility Ratio Effects", Trans. AIME (1958), 213, 356.

48. Paulsell, B.L.: "Areal Sweep Performance of Five-Spot Pilot Floods", M.Sc. Thesis, Penn. State University (Jan. 1958).

49. Perkins, F.M., Jr.,: "An Investigation of the Role of Capillary Forces in Laboratory Water Floods", Trans. AIME (1957), 210, 409.

50. Perkins, F.M., Jr. and Collins, R.E.: "Scaling Laws for Laboratory Flow Models of Oil Reservoirs", Trans. AIME (1960), 219,383.

51. Pirson, S.J.: "Oil Reservoir Engineering", McGraw-Hill Book Co. Inc. (1958).

52. Prats, M., Strickler, W.R., and Matthews, C.S.: "Single Fluid Five-Spot Floods in Dipping Reservoirs", Trans. AIME (1955), 204, 160.

53. Prats, M., Matthews, C.S., Jewett, R.L., and Baker, J.D.: "Prediction of Injection Rate and Production History for Multi-Fluid Five-Spot Floods", Trans. AIME (1959), 216, 98.

54. Ramey, H.J., Jr., and Nabor, G.W.: "A Blotter Type Electrolytic Model Determination of Areal Sweeps in Oil Recovery by In-S Combustion", Trans. AIME (1954), 201, 119.

55. Rappoport, L.A.: "Scaling Laws for Use in Design and Operation of Water-Oil Flow Models", Trans. AIME (1955),204, 143.

56. Rappoport, L.A., Carpenter, C.W., and Leas, W.J.: "Laboratory Studies of Five-Spot Waterflood Performance", Trans. AIME (1958), 213, 113.

57. Richardson, J.G., and Perkins, F.M., Jr.: "A Laboratory Investigation of the Effect of Rate on Recovery of Oil by Water Flooding", Trans. AIME (1957), 210, 115.

58. Scheidegger, A.E.: "The Physics of Flow Through Porous Media", the MacMillan Co., New York (1960).

59. Singhal, A.K.: "Simulation of Unconsolidated Porous Media", M.Sc. Thesis, University of Alberta, 1965.

60. Slobod, R.L. and Caudle, B.H.: "X-Ray Shadow Graph Studies of Areal Sweepout Efficiencies", Trans. AIME (1952), 195, 265.

61. Van Meurs, P.: "The Use of Transparent Three Dimensional Models for Studying the Mechanism of Flow Processes in Oil Reservoirs", Trans. AIME (1957), 210, 295.

62. Wyckoff, R.D., Botset, H.G., and Muskat, M.: "The Mechanics of Porous Flow Applied to Water Flooding Problems", Trans. AIME (1933), 103, 219.

63. Wygal, R.J.: "Construction of Models that Simulate Oil Reservoirs", SPE Jour. Dec. 1963.

APPENDIX

Table 1

Calculation of Effective Porosity by Material Balance Technique

$$\phi = \frac{V_p}{V_B}$$

where:

ϕ = effective porosity

V_p = interconnected pore volume

V_B = bulk volume of pack

$$V_B = \frac{\pi d^2 h}{4}$$

where

d = diameter of glass bead pack

= 33-3/4 inches

h = thickness of pack = ¼ inch

$$V_B = \frac{3.1416 \times (33\text{-}3/4)^2 \times (\tfrac{1}{4})}{4}$$

= 22.37 cu. in. = 3665 c.c.

V_p = fill up volume

= 1215 c.c.

$$\phi = \frac{1215}{3665}$$

ϕ = 33.2%

Table 2

Calculation of Porosity by Method of Paulsell

$$\phi = \frac{V_I}{16.386\ Ah}$$

where:

V_I = volume injected in c.c. = 84 c.c.

A = area swept out in inches = 63.8 sq. in.

h = height of pack in inches = ¼ in.

$$\phi = \frac{84}{63.8} \times \frac{4}{16.386}$$

$$\phi = 32.1\%$$

Table 3

Calculation of Effective Permeability to Water

Muskat's Equation for Five Spot

$$K_w = \frac{Q\mu_w(\log \frac{d}{r_w} - 0.619)}{0.003541\ \Delta Ph}$$

where:

K_w = effective permeability to water in millidarcys

Q = injection rate in barrels per day

μ_w = water viscosity in centipoises

d = distance from injection well to producing well, in feet

r_w = well bore radius in feet

ΔP = pressure differential in psi

h = formation thickness in feet

Model and Fluid Characteristics

Q = 0.290 B/D

ΔP = 6.545

h = 0.0208 ft.

μ_w = 0.8922 centipoises

d = 0.173 ft.

r_w = 0.00313 ft.

$\log \frac{d}{r_w}$ = 2.179

$$K_w = \frac{0.290 \times 0.8922 \times (2.179 - 0.619)}{0.003541 \times 6.545 \times 0.0208}\ \text{md}$$

K_w = 837 md

Table 4

Calculation of Effective Permeability to Oil

Muskat's Formula

$$K_o = \frac{Q\mu_o \left(\log \frac{d}{r_w} - 0.619\right)}{0.003541\ \Delta Ph}$$

where

K_o = effective permeability to oil

μ_o = viscosity of oil

and the other symbols are the same as in Table 3.

Model and Fluid Characteristics

Q = 0.121 B/D

ΔP = 0.884 psi

h = 0.0208

μ_w = 0.4673 centipoises

$\log \frac{d}{r_w}$ = 2.179

$$K_o = \frac{0.121 \times .4673\ (2.179 - 0.619)}{0.003541 \times (0.884) \times 0.0208}$$

K_o = 1,355 md

Table 5

Calculation of Pore Volume Within Five-Spot

Largest Five-Spot

$$PV = Ah\phi$$

where

A = area of five-spot = 144 sq. in.

= 929.0 sq. cm.

h = thickness = ¼ in.

ϕ = porosity = 33.2%

$PV = 144 \times \frac{1}{4} \times 16.386 \times 0.332 = 195.8$ c.c.

Smaller Five-Spot

A = 64 sq. in. = 412.9 sq. cm.

$PV = 64 \times \frac{1}{4} \times 16.386 \times 0.332 = 87.042$ c.c.

Calculation of Mobility Ratio

Properties

$$K_w = 837 \text{ md}$$

$$\mu_w = 0.8922 \text{ cps}$$

$$K_o = 1355 \text{ md}$$

$$\mu_o = 0.4673 \text{ cps}$$

$$M = \frac{\lambda_w}{\lambda_o}$$

$$\lambda_w = \frac{K_w}{\mu_w} = \frac{837}{0.8922} = 938 \text{ md/cps}$$

$$\lambda_o = \frac{K_w}{\mu_w} = \frac{135}{0.4673} = 290 \text{ md/cps}$$

$$M = \frac{938}{290} = 0.324$$

Table 7

Determination of Apparent Contact Angle

The results and a sample calculation for the determination of apparent contact angle are given below. The technique employed was developed by Singhal(57).

a) Capillary Pressure

Data:

Deflections - 0.95 cm and 1.70 cm

Input voltage - 10 volts

Calibration factor of pressure transducer

- 136.3 microvolts/volt/psi

Calibration factor of dynograph - 0.2 millivolts/cm

$$\text{Overall factor} = \frac{0.2 \text{ millivolts/cm}}{10 \text{ volts} \times 136.3 \text{ microvolts/volt/psi}}$$

$$= 0.1467 \text{ psi/cm}$$

$$\text{Capillary pressure} = (1.50 - 0.81) \text{ cm}$$

$$= 0.69 \times 0.1467 \text{ psi}$$

$$= 0.101 \text{ psi}$$

b) Interfacial Tension

The value of the interfacial tension between the oil and the flooding water at 78^{o}F was found to be 45.86 dynes/cm.

Table 7 (continued)

c) Porosity

Weight of pack = (1496.020 - 1350.180) gms

= 145.840 gms

Height of pack = (4.543 - 1.005) in.

= 3.538 in.

= 8.99 cm

Cross-sectional area of pack = 10.463 sq.cm.

Volume of pack = 10.463 x 8.99 cc

= 94.062 cc

$$\text{Apparent density } (\rho_a) = \frac{145.840 \text{ gm}}{94.062 \text{ cc}}$$

$$= 1.550 \text{ gm/cc}$$

$$\text{Porosity } (\phi) = \frac{\rho_g - \rho_a}{\rho_g}$$

$$= 2.442 \text{ gm/cc}$$

$$\phi = \frac{2.442 - 1.550}{2.442}$$

$$= 36.53\%$$

d) Permeability

Darcy's Law:

$$Q = \frac{AK\Delta P}{\mu l}$$

Table 7 (continued)

$$K = \frac{Q\mu L}{A\Delta P}$$

$$Q = \frac{320}{60 \times 60} \text{ cc/sec.}$$

$$A = 10.463 \text{ sq.cm.}$$

$$\mu = 0.8922 \text{ cps}$$

$$L = 8.87 \text{ cm}$$

$$\Delta P = 0.81 \text{ cm.} \times 0.1467 \text{ psi/cm.} \times 0.0680 \text{ atms/psi}$$

$$= 0.00808 \text{ atms}$$

$$K = \frac{320 \times 0.8922 \times 8.99}{60 \times 60 \times 10.463 \times .00808}$$

$$K = 8.43 \text{ darcies}$$

e) The Apparent Contact Angle

Using the above results to calculate the product

$$C_2 = \frac{\Delta P}{\sigma_{IT}} \sqrt{\frac{K}{\phi}}$$

the product (C_2) becomes

$$C_2 = \frac{.101}{45.86} \sqrt{\frac{8.43}{36.53}} = 1.135 \times 10^{-3}$$

This is the value of the product for the cleanest possible beads and the assumption is made that these beads have a

Table 7 (continued)

contact angle of 0°.

Calculating the product (C_2) for a sample of beads taken from the model after all runs were completed; the value of the product was found to be 1.074×10^{-3}.

Hence, the wettability index

$$\cos\theta = \frac{1.074 \times 10^{-3}}{1.135 \times 10^{-3}}$$

$$= \underline{0.94625}$$

$$= 19^{\circ}$$

Table 8

Production History - Five-Spot Flood 1-C

Injection Rate = 400 cc/hr/well   Back pressure = 0 psig

Oil in Place = 735 cc   d = 12 in.

(1) Total Cum. Prod. (cc)	(2) Cum. Oil Prod. (cc)	(3) Cum. Water Prod. (cc)	(4) Through-Put in 5-Spot P.V.	(5) Inst. W.O.R.	(6) Oil Rec. in 5-Spot H.C.P.V.	(7) Oil Rec. % Oil in Place
35	35	0	0.179	-	0.30	4.76
97	97	0	0.495	-	0.83	13.97
231	231	0	1.18	-	1.97	31.43
477	477	0	2.44	-	4.06	64.90
560	560	0	2.86	WBT	4.77	76.19
618	602	16	3.16	0.381	5.12	81.90
628	609	19	3.21	0.429	5.18	82.86
649	626	23	3.31	0.235	5.33	85.17
673.6	635.6	38	3.44	1.56	5.41	86.48
698.6	644.3	54.3	3.57	1.87	5.49	87.66
723.6	651.3	72.3	3.70	2.57	5.54	88.61
748.5	657.4	91.1	3.82	3.08	5.60	89.44
772.9	661.8	111.1	3.95	4.55	5.63	90.04
797.9	664.9	133.0	4.08	7.06	5.66	90.46
821.3	666.9	154.4	4.19	10.7	5.68	90.73
846.3	668.3	178.0	4.32	16.9	5.69	90.93
870.9	669.6	201.3	4.45	17.9	5.70	91.10
895.7	670.6	225.1	4.57	23.8	5.71	91.24
920.7	671.5	249.2	4.70	26.8	5.71	91.36
945.5	672.3	273.2	4.83	30.0	5.72	91.47
970.5	673.0	297.5	4.96	34.7	5.73	91.56
995.5	673.6	321.9	5.08	40.7	5.73	91.65
1020.5	674.1	346.4	5.21	49.0	5.74	91.71

Table 9

Five-Spot Flood 1-C

Calculation of Areal Sweep Efficiency (E_{as})

Injection Rate = 400 cc/hr/well

Back Pressure = 0 psig

d = 12 inches

(1) Cumulative Through-Put (P.V.)	(2) Area Swept Out (sq.cm.)	(3) E_{as} Area Swept/Unit Area (Fraction)
0.179	527	0.567
0.495	1223	1.32
1.18	2217	2.39
2.44	3597	3.87
3.21	4290	4.62
3.95	-	5.59*
5.08	-	5.69*

* Calculated Values

Table 10

Production History - Five-Spot Flood 2-A

Injection Rate = 320 cc/hr/well   Back pressure = .0151 psig

Oil in place = 803 cc   d = 8 in.

(1) Total Cum. Prod. (cc)	(2) Cum. Oil Prod. (cc)	(3) Cum. Water Prod. (cc)	(4) Through-Put in 5-Spot P.V.	(5) Inst. W.O.R.	(6) Oil Rec. in 5-Spot H.C.P.V.	(7) Oil Rec. % Oil in Place
30	30	0	0.345	-	.57	3.74
70	70	0	0.804	-	1.34	8.71
100	100	0	1.148	-	1.91	12.45
182	182	0	2.09	-	3.48	22.67
350	350	0	4.02	-	6.70	43.59
392	392	0	4.50	-	7.51	48.82
587	587	0	6.74	WBT	11.24	73.10
600	600	Trace	6.89	-	11.49	74.72
631	627	4	7.25	0.13	12.01	78.08
658	651	7	7.56	0.125	12.47	81.07
707	682.5	24.5	8.12	0.556	13.07	84.99
756	705.5	50.5	8.69	1.13	13.51	87.86
806	724.5	81.5	9.26	1.63	13.87	90.22
856	736.5	119.5	9.83	3.17	14.10	91.72
906	746.0	160.0	10.41	4.26	14.28	92.90
955	754.2	200.8	10.97	5.10	14.44	93.92
1004	760.2	243.8	11.53	7.17	14.56	94.67
1054	765.7	288.3	12.11	8.09	14.66	95.35
1103.5	770.2	333.3	12.67	10.00	14.75	95.92
1153.5	774.2	379.3	13.25	11.50	14.82	96.41
1203.5	777.7	425.8	13.82	13.29	14.89	96.86
1227.0	779.2	447.8	14.10	14.67	14.92	97.04
1246.8	780.2	466.6	14.32	18.80	14.94	97.16
1266.0	781.1	484.9	14.54	20.33	14.96	97.27
1285.2	782.0	503.2	14.76	20.33	14.97	97.38
1304.4	782.9	521.5	14.99	20.33	14.99	97.50
1319.0	783.3	535.7	15.15	35.50	15.00	97.55
1336.0	784.1	551.9	15.34	20.25	15.01	97.65

Table 11

Five-Spot Flood 2-A

Calculation of Areal Sweep Efficiency (E_{as})

Injection Rate = 320 cc/hr/well

Back Pressure = .0151 psig

d = 8 inches

(1) Cumulative Through-Put (P.V.)	(2) Area Swept Out (sq.cm.)	(3) E_{as} Area Swept/Unit Area (Fraction)
0.345	438	1.06
0.804	801	1.94
2.09	1594	3.86
4.50	2820	6.83
7.25	3823	9.26
8.12	4563	11.05
10.41	-	12.91*
13.25	-	13.40*
15.34	-	13.60*

* Calculated Values

Table 12

Production History - Five-Spot Flood 2-B

Injection Rate = 400 cc/hr/well   Back pressure = .0151 psig

Oil in Place = 790 cc   d = 8 in.

(1) Total Cum. Prod. (cc)	(2) Cum. Oil Prod. (cc)	(3) Cum. Water Prod. (cc)	(4) Through-Put in 5-Spot P.V.	(5) Inst. W.O.R.	(6) Oil Rec. in 5-Spot H.C.P.V.	(7) Oil Rec. % Oil in Place
50	50	0	.574	-	0.96	6.33
347	347	0	3.99	-	6.64	43.92
608	608	0	6.99	-	11.64	76.96
636.2	635.1	9.1	7.31	WBT	12.16	80.39
660.3	642.2	18.1	7.59	0.336	12.55	82.94
684.3	654.2	30.1	7.86	0.448	12.78	84.46
708.8	661.5	47.3	8.14	1.00	12.92	85.38
719.0	663.7	55.3	8.26	2.36	12.96	85.66
728.8	665.7	63.1	8.37	3.64	13.00	85.91
742.0	669.1	73.9	8.52	3.90	13.04	86.22
753.7	670.4	83.3	8.66	4.50	13.09	86.46
765.7	672.2	93.5	8.80	4.09	13.12	86.73
778.1	674.2	103.9	8.94	5.67	13.15	86.96
789.3	676.8	112.5	9.07	5.20	13.20	87.29
806.9	679.2	127.7	9.27	3.30	13.25	87.59
816.6	680.2	136.4	9.38	6.33	13.27	87.72
829.6	681.4	147.8	9.53	8.70	13.30	87.92
854.6	684.4	170.2	9.82	7.12	13.35	88.25
868.0	684.6	183.4	9.98	8.66	13.38	88.46
884.6	686.0	198.6	10.14	8.81	13.65	90.23

Table 13

Five-Spot Flood 2-B

Calculation of Areal Sweep Efficiency (E_{as})

Injection Rate = 400 cc/hr/well

Back Pressure = .0151 psig

d = 8 inches

(1) Cumulative Through-Put (P.V.)	(2) Area Swept Out (sq.cm.)	(3) E_{as} Area Swept/Unit Area (Fraction)
0.96	541	1.31
2.40	1594	3.86
3.99	2861	6.93
6.80	3997	9.68
10.14	-	12.5*

* Calculated Values

Table 14

Production History - Five-Spot Flood 2-C

Injection Rate = 480 cc/hr/well Back pressure = .0151 psig

Oil in Place = 732 cc d = 8 in.

(1) Total Cum. Prod. (cc)	(2) Cum. Oil Prod. (cc)	(3) Cum. Water Prod. (cc)	(4) Through-Put in 5-Spot P.V.	(5) Inst. W.O.R.	(6) Oil Rec. in 5-Spot H.C.P.V.	(7) Oil Rec. % Oil in Place
55	55	0	0.63	-	1.05	7.51
176	176	0	2.02	-	3.37	24.04
375	375	0	4.31	-	7.18	51.23
495	495	0	5.69	-	9.48	67.62
500	499	1	5.74	WBT	9.56	68.17
575	559	16	6.61	-	10.70	76.37
600	575.8	24.2	6.90	0.488	11.03	78.66
624.6	592.0	32.6	7.18	0.519	11.34	80.87
649.2	607.6	41.6	7.46	0.577	11.64	83.01
672.2	620.6	51.6	7.61	0.769	11.89	84.78
696.2	632.4	63.8	8.00	1.03	12.11	86.39
719.8	643.2	76.6	8.27	1.19	12.32	87.87
744.0	652.0	92.0	8.55	1.75	12.49	89.07
769.0	659.6	109.4	8.84	2.29	12.64	90.10
792.6	665.8	126.8	9.11	2.81	12.75	90.96
816.4	670.8	145.6	9.38	3.76	12.85	91.63
839.8	675.2	164.6	9.65	4.31	12.93	92.24
865.6	679.6	186.0	9.94	4.86	13.02	92.84
890.8	683.4	207.4	10.23	5.63	13.09	93.36
915.0	686.8	228.2	10.42	6.12	13.16	93.83
939.0	690.2	248.8	10.79	6.06	13.22	94.29
964.0	693.6	270.4	11.08	6.35	13.29	94.75
985.2	696.0	289.2	11.35	7.83	13.33	95.08
996.2	697.1	299.1	11.47	9.00	13.35	95.23
1005.4	697.9	307.5	11.57	10.50	13.37	95.34
1027.2	699.9	327.3	11.83	9.90	13.41	95.61
1075.2	702.9	372.3	12.38	15.0	13.47	96.02
1100.9	704.9	396.0	12.67	11.85	13.50	96.30
1124.9	706.7	418.2	12.95	12.3	13.54	96.54
1151.5	708.3	443.2	13.23	15.6	13.57	96.76
1175.8	708.8	467.0	13.53	47.6	13.58	96.83
1211.9	709.6	502.3	13.94	44.1	13.59	96.93

Table 15

Five-Spot Flood 2-C

Calculation of Areal Sweep Efficiency (E_{as})

Injection Rate = 480 cc/hr/well

Back Pressure = .0151 psig

d = 8 inches

(1) Cumulative Through-Put (P.V.)	(2) Area Swept Out (sq.cm.)	(3) E_{as} Area Swept/Unit Area (Fraction)
0.632	694	1.68
2.02	1449	3.51
4.31	2750	6.66
6.61	4051	9.81
9.94	-	12.90*
11.83	-	13.29*
13.94	-	13.47*

* Calculated Values

Table 16

Production History - Five-Spot Flood 2-D

Injection Rate = 800 cc/hr/well   Back pressure = .0151 psig

Oil in Place = 791 cc   d = 8 in.

(1) Total Cum. Prod. (cc)	(2) Cum. Oil Prod. (cc)	(3) Cum. Water Prod. (cc)	(4) Through-Put in 5-Spot P.V.	(5) Inst. W.O.R.	(6) Oil Rec. in 5-Spot H.C.P.V.	(7) Oil Rec. % Oil in Place
77	77	0	0.885	-	1.47	9.73
162	162	0	1.86	-	3.10	20.48
472	472	0	5.42	-	9.04	59.67
545	545	0	6.26	WBT	10.43	68.90
612	600	12	7.03	0.218	11.49	75.85
642	627	15	7.38	0.111	12.01	79.27
742	693	49	8.52	0.872	13.27	87.61
774	699	75	8.89	4.33	13.38	88.37
798	702.2	95.8	9.17	6.50	13.45	88.77
821.4	705.0	116.4	9.44	7.36	13.50	89.13
845.6	708.0	137.6	9.70	7.06	13.52	89.25
859.4	709.6	149.8	9.86	7.62	13.55	89.46
883.2	711.4	171.8	10.14	12.2	13.58	89.68
895.4	712.5	182.9	10.27	10.0	13.60	89.82
906.2	713.8	195.1	10.40	10.2	13.63	89.99
921.7	714.9	206.9	10.57	10.7	13.65	90.13
936.4	716.1	220.3	10.75	11.2	13.67	90.28
946.4	716.9	229.5	10.86	11.5	13.69	90.38
958.8	718.0	240.8	11.00	10.2	13.71	90.52
970.6	719.0	251.6	11.14	10.8	13.73	90.64
983.6	720.0	263.6	11.29	12.0	13.75	90.77
997.4	720.7	276.7	11.45	18.7	13.76	90.86

Table 17

Five-Spot Flood 2-D

Calculation of Areal Sweep Efficiency (E_{as})

Injection Rate = 800 cc/hr/well

Back Pressure = .0151 psig

d = 8 inches

(1) Cumulative Through-Put (P.V.)	(2) Area Swept Out (sq.cm.)	(3) E_{as} Area Swept/Unit Area (Fraction)
0.885	533	1.29
1.86	1313	3.18
5.42	3283	7.95
7.38	4249	10.29
9.86	-	12.43*
10.86	-	12.56*
11.45	-	12.63*

* Calculated Values

Table 18

Production History - Five-Spot Flood 3-A

Injection Rate = 480 cc/hr/well   Back pressure = 0 psig

Oil in Place = 720 cc   d = 8 in.

(1) Total Cum. Prod. (cc)	(2) Cum. Oil Prod. (cc)	(3) Cum. Water Prod. (cc)	(4) Through-Put in 5-Spot P.V.	(5) Inst. W.O.R.	(6) Oil Rec. in 5-Spot H.C.P.V.	(7) Oil Rec. % Oil in Place
54	54	0	0.620	-	1.03	7.5
164	164	0	1.88	-	3.14	22.8
247	247	0	2.84	-	4.73	34.3
447	447	0	5.14	WBT	8.56	62.1
465	465	trace	5.34	-	8.90	64.6
508	500.5	7.5	5.84	0.211	9.58	69.5
600	574.5	25.5	6.89	0.243	11.00	79.8
651.3	608.0	43.3	7.48	0.531	11.64	84.4
700.3	631.9	68.4	8.05	1.05	12.10	87.8
749.8	648.4	101.4	8.61	2.00	12.42	90.1
799.8	660.9	138.9	9.19	3.00	12.65	91.8
848.8	670.2	178.6	9.75	4.27	12.83	93.1
896.3	676.4	219.9	10.30	6.66	12.95	93.9
943.2	682.1	261.1	10.84	7.23	13.06	94.7
992.7	686.4	306.3	11.40	10.51	13.14	95.3
1041.7	689.7	352.0	11.97	13.85	13.21	95.8
1090.5	693.2	397.3	12.53	12.94	13.27	96.3
1139.5	696.0	443.5	13.09	16.50	13.33	96.7
1193.1	699.6	493.5	13.70	13.89	13.40	97.2
1241.2	702.5	538.7	14.26	15.59	13.45	97.6
1264.8	703.3	561.5	14.53	28.50	13.47	97.7
1288.5	704.1	584.4	14.80	28.86	13.48	97.8
1312.1	704.7	607.4	15.07	38.33	13.49	97.9
1335.8	705.4	630.4	15.35	32.86	13.51	98.0
1359.2	706.0	653.2	15.62	38.00	13.52	98.0
1384.1	706.6	677.5	15.90	40.50	13.53	98.1
1407.6	707.1	700.5	16.17	46.00	13.54	98.2

Table 19

Five-Spot Flood 3-A

Calculation of Areal Sweep Efficiency (E_{as})

Injection Rate = 480 cc/hr/well

Back Pressure = 0 psig

d = 8 inches

(1) Cumulative Through-Put (P.V.)	(2) Area Swept Out (sq.cm.)	(3) E_{as} Area Swept/Unit Area (Fraction)
0.620	487	1.18
1.88	1210	2.94
4.10	2950	7.15
5.84	3650	8.85
8.05	-	12.2*
10.3	-	13.0*
16.17	-	13.6*

* Calculated Values

Table 20

Production History - Five-Spot Flood 3-B

Injection Rate = 480 cc/hr/well   Back pressure = .0151 psig

Oil in Place = 740 cc   d = 8 in.

(1) Total Cum. Prod. (cc)	(2) Cum. Oil Prod. (cc)	(3) Cum. Water Prod. (cc)	(4) Through-Put in 5-Spot P.V.	(5) Inst. W.O.R.	(6) Oil Rec. in 5-Spot H.C.P.V.	(7) Oil Rec. % Oil in Place
24	24	0	0.276	-	0.46	3.2
52	52	0	0.597	-	1.00	7.0
170	170	0	1.95	-	3.26	23.0
380	380	0	4.37	-	7.28	51.4
490	490	0	5.63	WBT	9.38	66.2
496	493	3	5.70	1 00	9.44	66.6
561	553	8	6.45	0.0877	10.59	74.7
595	582.5	12.5	6.84	0.153	11.15	78.7
691	641.5	49.5	7.94	0.627	12.28	86.7
737	662.5	74.5	8.47	1.19	12.69	89.5
777	673.5	103.5	8.93	2.64	12.90	91.0
814	682.0	132.0	9.35	3.35	13.06	92.2
852.5	689.5	163.0	9.79	4.13	13.20	93.2
891.0	695.0	196.0	10.24	6.00	13.31	93.9
930.0	700.0	230.0	10.68	6.80	13.40	94.6
968.5	704.3	264.2	11.13	7.95	13.49	95.2
994.0	707.3	286.7	11.42	7.50	13.54	95.6
1017.8	709.3	308.5	11.69	10.90	13.58	95.9
1043.2	711.3	331.9	11.99	11.70	13.62	96.1
1067.6	713.3	354.3	12.27	11.20	13.66	96.4
1091.6	714.9	376.7	12.54	14.00	13.69	96.6
1115.8	716.1	399.7	12.82	19.17	13.71	96.8
1140.7	717.4	423.3	13.11	18.15	13.74	96.9
1160.9	718.2	442.7	13.34	24.25	13.75	97.0
1180.7	718.8	461.9	13.56	32.00	13.76	97.1
1200.3	719.2	481.1	13.79	48.00	13.77	97.2
1221.2	720.1	501.1	14.03	22.22	13.79	97.3
1239.8	720.9	518.9	14.24	22.25	13.80	97.4
1259.8	721.5	538.3	14.47	32.33	13.82	97.5
1284.0	722.1	561.9	14.75	39.33	13.83	97.6

Table 21

Five-Spot Flood 3-B

Calculation of Areal Sweep Efficiency (E_{as})

Injection Rate = 480 cc/hr/well

Back Pressure = .0151 psig

d = 8 inches

(1) Cumulative Through-Put (P.V.)	(2) Area Swept Out (sq.cm.)	(3) E_{as} Area Swept/Unit Area (Fraction)
0.276	359	0.869
0.597	657	1.59
1.95	1350	3.27
4.37	2795	6.77
6.45	4059	9.83
10.24	-	13.05*
12.27	-	13.40*
14.75	-	13.60*

* Calculated Values

Table 22

Production History - Five-Spot Flood 3-C

Injection Rate = 480 cc/hr/well   Back pressure = .0277 psig

Oil in Place = 763 cc   d = 8 in.

(1) Total Cum. Prod. (cc)	(2) Cum. Oil Prod. (cc)	(3) Cum. Water Prod. (cc)	(4) Through-Put in 5-Spot P.V.	(5) Inst. W.O.R.	(6) Oil Rec. in 5-Spot H.C.P.V.	(7) Oil Rec. % Oil in Place
58	58	0	0.666	-	1.11	7.6
188	188	0	2.15	-	3.60	24.6
250	250	0	2.87	-	4.79	32.8
366	366	0	4.20	-	7.01	48.0
498	498	0	5.72	-	9.54	65.3
543	543	0	6.24	WBT	10.40	71.2
585	575	10	6.72	.312	11.01	75.4
614.8	599.8	15	7.06	.202	11.48	78.6
669.8	641.0	28.8	7.70	.335	12.27	84.0
718.6	665.8	52.8	8.26	.968	12.74	87.3
768.6	683.2	85.4	8.83	1.87	13.08	89.5
817.8	695.2	122.6	9.40	3.10	13.31	91.1
866.7	704.3	162.4	9.96	4.37	13.49	92.3
915.5	711.6	203.9	10.52	5.68	13.63	93.3
963.4	717.7	245.7	11.07	6.85	13.74	94.1
1011.5	722.8	288.7	11.62	8.43	13.84	94.7
1059.6	726.7	332.9	12.17	11.3	13.91	95.2
1106.6	730.7	375.9	12.71	10.8	13.99	95.8
1154.7	734.3	420.4	13.26	12.4	14.06	96.2
1203.2	737.0	466.2	13.82	17.0	14.11	96.6
1251.1	739.8	511.3	14.37	16.1	14.17	97.0
1299.0	742.5	556.5	14.92	16.7	14.22	97.3
1336.3	744.3	592.0	15.35	19.7	14.25	97.5
1355.7	745.1	610.6	15.58	23.3	14.27	97.7
1374.3	745.9	628.4	15.79	22.3	14.28	97.8
1393.3	746.6	646.7	16.01	26.1	14.30	97.9

Table 23

Five-Spot Flood 3-C

Calculation of Areal Sweep Efficiency (E_{as})

Injection Rate = 480 cc/hr/well

Back Pressure = .0277 psig

d = 8 inches

(1) Cumulative Through-Put (P.V.)	(2) Area Swept Out (sq.cm.)	(3) E_{as} Area Swept/Unit Area (Fraction)
0.666	574	1.39
2.15	1510	3.66
4.20	2510	6.09
6.72	4070	9.85
9.40	-	12.6*
11.07	-	13.0*
16.01	-	13.6*

* Calculated Values

Table 24

Production History - Five-Spot Flood 3-D

Injection Rate = 480 cc/hr/well   Back Pressure = .0403 psig

Oil in Place = 810 cc   d = 8 in.

(1) Total Cum. Prod. (cc)	(2) Cum. Oil Prod. (cc)	(3) Cum. Water Prod. (cc)	(4) Through-Put in 5-Spot P.V.	(5) Inst. W.O.R.	(6) Oil Rec. in 5-Spot H.C.P.V.	(7) Oil Rec. % Oil in Place
38	38	0	0.437	-	0.73	4.7
134	134	0	1.54	-	2.57	16.5
250	250	0	2.87	-	4.79	30.9
336	336	0	3.86	-	6.43	41.5
500	500	0	5.74	-	9.57	61.7
588	588	0	6.76	-	11.26	72.6
600	600	0	6.89	-	11.49	74.1
700	700	0	8.04	-	13.40	86.4
730	730	0	8.39	WBT	13.98	90.1
749	748	1	8.61	0.0556	14.32	92.3
783	768	15	9.00	0.700	14.70	94.8
798	777	21	9.17	0.667	14.88	95.9
845.5	790.6	54.9	9.71	2.42	15.14	97.6
907.3	797.9	109.4	10.42	7.47	15.28	98.5
954.4	800.8	153.6	10.96	15.2	15.33	98.9
1004.4	803.0	201.4	11.54	21.7	15.38	99.1
1055.4	804.2	251.2	12.12	41.5	15.40	99.3

Table 25

Five-Spot Flood 3-D

Calculation of Areal Sweep Efficiency (E_{as})

Injection Rate = 480 cc/hr/well

Back Pressure = .0403 psig

d = 8 inches

(1) Cumulative Through-Put (P.V.)	(2) Area Swept Out (sq.cm.)	(3) E_{as} Area Swept/Unit Area (Fraction)
0.437	562	1.75
1.54	1840	4.46
3.86	3430	8.31
6.76	5020	12.2
9.00	5570	13.5
10.42	-	13.8*
12.12	-	13.9*

*Calculated Values

Table 26

Production History - Five-Spot Flood 3-E

Injection Rate = 480 cc/hr/well   Back pressure = .0655 psig

Oil in Place = 812 cc   d = 8 in.

(1) Total Cum. Prod. (cc)	(2) Cum. Oil Prod. (cc)	(3) Cum. Water Prod. (cc)	(4) Through-Put in 5-Spot P.V.	(5) Inst. W.O.R.	(6) Oil Rec. in 5-Spot H.C.P.V.	(7) Oil Rec. % Oil in Place
52	52	0	0.597	0	1.00	6.4
137	137	0	1.57	0	2.62	16.9
250	250	0	2.87	0	4.79	30.8
328	328	0	3.77	0	5.90	40.4
500	500	0	5.74	0	9.57	61.6
560	560	0	6.43	0	10.72	69.0
575	575	0	6.61	WBT	11.01	70.8
598	594	4	6.87	0.210	11.37	73.2
647	635	12	7.43	0.195	12.15	78.2
688	668	20	7.90	0.242	12.79	82.3
738	691.2	46.8	8.48	1.15	13.24	85.1
812.3	711.2	101.1	9.34	2.72	13.62	87.6
857.3	718.9	138.4	9.85	4.84	13.77	88.5
903.5	726.6	176.9	10.38	5.00	13.91	89.5
950.2	732.4	217.8	10.92	7.05	14.02	90.2
998.0	738.7	259.3	11.47	6.60	14.14	91.0
1038.9	743.4	295.5	11.94	7.80	14.23	91.6
1083.0	747.7	335.3	12.44	9.22	14.32	92.1
1123.8	751.2	372.6	12.91	10.6	14.38	92.5
1144.3	752.7	391.6	13.15	12.7	14.41	92.7
1165.0	754.0	411.0	13.38	13.8	14.44	92.9
1190.8	756.1	434.6	13.68	15.1	14.48	93.1
1210.7	757.3	453.4	13.91	15.6	14.50	93.3
1234.4	758.7	475.7	14.18	15.9	14.53	93.4
1254.5	759.8	494.7	14.41	17.3	14.55	93.6
1273.8	760.7	513.1	14.64	20.4	14.57	93.7
1294.2	761.5	532.7	14.87	24.5	14.58	93.8

Table 27

Five-Spot Flood 3-E

Calculation of Areal Sweep Efficiency (E_{as})

Injection Rate = 480 cc/hr/well

Back Pressure = .0655 psig

d = 8 inches

(1) Cumulative Through-Put (P.V.)	(2) Area Swept Out (sq.cm.)	(3) E_{as} Area Swept/Unit Area (Fraction)
0.597	483	1.17
1.57	1140	2.75
3.77	2230	5.41
6.43	3640	8.81
7.43	4038	9.78
9.85	-	12.3*
14.6	-	13.0*

* Calculated Values

Table 28

Production History - Five-Spot Flood 3-F

Injection Rate = 480 cc/hr/well   Back pressure = .101 psig

Oil in Place = 855 cc   d = 8 in.

(1) Total Cum. Prod. (cc)	(2) Cum. Oil Prod. (cc)	(3) Cum. Water Prod. (cc)	(4) Through-Put in 5-Spot P.V.	(5) Inst. W.O.R.	(6) Oil Rec. in 5-Spot H.C.P.V.	(7) Oil Rec. & Oil in Place
45	45	0	0.517	-	0.86	5.3
126	126	0	1.45	-	2.41	14.7
248	248	0	2.85	-	4.75	29.0
332	332	0	3.81	-	6.36	38.8
498	498	0	5.72	-	9.54	58.2
526	526	0	6.04	-	10.07	61.5
563	563	0	6.47	WBT	10.78	65.8
598	593	5	6.87	0.167	11.35	69.4
650	632	18	7.47	0.333	12.10	73.9
715.5	653	62.5	8.22	2.12	12.50	76.4
762.5	662.5	100.0	8.76	3.95	12.69	77.5
809.1	669.5	139.6	9.30	5.66	12.82	78.3
857.2	675.8	181.4	9.85	6.63	12.94	79.0
902.9	681.5	221.4	10.37	7.02	13.05	79.7
949.1	686.5	262.6	10.90	8.24	13.15	80.3
995.1	690.6	304.5	11.43	10.22	13.22	80.8
1041.4	694.3	347.1	11.96	11.51	13.29	81.2
1084.8	697.7	387.1	12.46	11.76	13.36	81.6
1127.9	700.6	427.3	12.96	13.86	13.42	81.9
1147.7	702.2	445.5	13.19	11.38	13.45	82.1
1167.5	703.6	463.9	13.41	13.14	13.47	82.3
1187.7	704.9	482.8	13.65	14.54	13.50	82.4
1207.5	706.1	501.4	13.87	15.50	13.52	82.6
1227.8	707.0	520.8	14.10	21.56	13.54	82.7

Table 29

Five-Spot Flood 3-F

Calculation of Areal Sweep Efficiency (E_{as})

Injection Rate = 480 cc/hr/well

Back Pressure = .101 psig

d = 8 inches

(1) Cumulative Through-Put (P.V.)	(2) Area Swept Out (sq.cm.)	(3) E_{as} Area Swept/Unit Area (Fraction)
0.517	446	1.08
1.45	1030	2.50
3.81	2230	5.39
6.04	3310	8.02
6.87	3560	8.62
10.37	-	11.1*
14.1	-	11.5*

* Calculated Values

Table 30

Production History - Five-Spot Flood 3-G

Injection Rate = 480 cc/hr/well Back pressure ?(plug off)

Oil in Place = 860 cc d = 8 in.

(1) Total Cum. Prod. (cc)	(2) Cum. Oil Prod. (cc)	(3) Cum. Water Prod. (cc)	(4) Through-Put in 5-Spot P.V.	(5) Inst. W.O.R.	(6) Oil Rec. in 5-Spot H.C.P.V.	(7) Oil Rec. % Oil in Place
30	30	0	0.344	-	0.57	3.5
82	82	0	0.942	-	1.57	9.5
168	168	0	1.93	-	3.22	19.5
248	248	0	2.85	-	4.75	28.8
418	418	0	4.80	-	8.00	48.6
498	498	0	5.72	-	9.54	57.9
581	581	0	6.67	-	11.12	67.6
593	593	0	6.81	WBT	11.35	69.0
596	596	Trace	6.85	-	11.41	69.3
653.5	620	33.5	7.51	1.40	11.87	72.1
705.0	627.5	77.5	8.10	5.87	12.02	73.0
753.0	631.5	121.5	8.65	11.0	12.09	73.4
803.0	635.5	167.5	9.23	11.5	12.17	73.8
852.0	638.5	213.5	9.79	15.3	12.23	74.2
898.5	641.0	257.5	10.32	17.6	12.27	74.5
945.6	643.6	302.0	10.86	17.1	12.32	74.8
990.1	645.1	345.0	11.37	28.6	12.35	75.0
1037.6	647.6	390.0	11.92	17.0	12.40	75.3
1086.1	649.6	436.5	12.48	23.2	12.44	75.6
1109.1	650.6	458.5	12.74	22.0	12.46	75.7
1128.3	651.4	476.9	12.96	22.5	12.47	75.7
1144.6	652.1	492.5	13.15	22.3	12.49	75.8
1169.3	652.6	516.7	13.43	48.4	12.50	75.9

Table 31

Five-Spot Flood 3-G

Calculation of Areal Sweep Efficiency (E_{as})

Injection Rate = 480 cc/hr/well

Back Pressure = ? (Plug Off)

d = 8 inches

(1) Cumulative Through-Put (P.V.)	(2) Area Swept Out (sq.cm.)	(3) E_{as} Area Swept/Unit Area (Fraction)
0.344	303	0.735
0.942	718	1.74
1.93	1330	3.22
4.80	2650	6.41
6.67	3460	8.39
7.51	3766	9.12
8.65	-	10.2*
11.37	-	10.4*
13.43	-	10.6*

* Calculated Values

Table 32

Production History - Five-Spot Flood 3-H

Injection Rate = 480 cc/hr/well   Back pressure = .116 psig

Oil in Place = 908 cc   d = 8 in.

(1) Total Cum. Prod. (cc)	(2) Cum. Oil Prod. (cc)	(3) Cum. Water Prod. (cc)	(4) Through-Put in 5-Spot P.V.	(5) Inst. W.O.R.	(6) Oil Rec. in 5-Spot H.C.P.V.	(7) Oil Rec. % Oil in Place
43	43	0	.495	-	0.82	4.74
109	109	0	1.25	-	2.09	12.0
250	250	0	2.87	-	4.79	27.5
257	257	0	2.95	-	4.92	28.3
350	350	0	4.02	-	6.70	38.5
450	450	0	5.17	-	8.62	49.6
506	506	0	5.81	-	9.69	55.7
606	606	0	6.96	WBT	11.60	66.7
638	633	5	7.33	0.185	12.12	69.7
670	644	26	7.70	1.91	12.33	70.9
719	657	62	8.26	2.77	12.58	72.4
769	662	107	8.83	9.0	12.68	72.9
818.5	665.5	153	9.40	13.1	12.74	73.2
865.5	668.5	197	9.94	14.7	12.80	73.6
912.0	670.5	241.5	10.48	22.3	12.84	73.8
961.4	672.4	289.0	11.04	25.0	12.88	74.1
997.9	673.7	324.2	11.46	27.1	12.90	74.2
1034.0	674.2	359.8	11.87	71.2	12.91	74.3
1069.8	674.6	395.2	12.28	88.5	12.92	74.3
1090.3	674.8	415.5	12.40	101.5	12.92	74.3
1109.5	675.0	434.5	12.73	95.0	12.92	74.3
1147.7	675.3	472.4	13.18	126.3	12.93	74.4

Table 33

Five-Spot Flood 3-H

Calculation of Areal Sweep Efficiency (E_{as})

Injection Rate = 480 cc/hr/well

Back Pressure = .116 psig

d = 8 inches

(1) Cumulative Through-Put (P.V.)	(2) Area Swept Out (sq.cm.)	(3) E_{as} Area Swept/Unit Area (Fraction)
0.495	442	1.07
1.25	962	2.33
2.95	1820	4.40
5.81	3110	7.53
7.33	3590	8.70
9.61	3960	9.59
12.93	-	10.15*

* Indicates calculated point

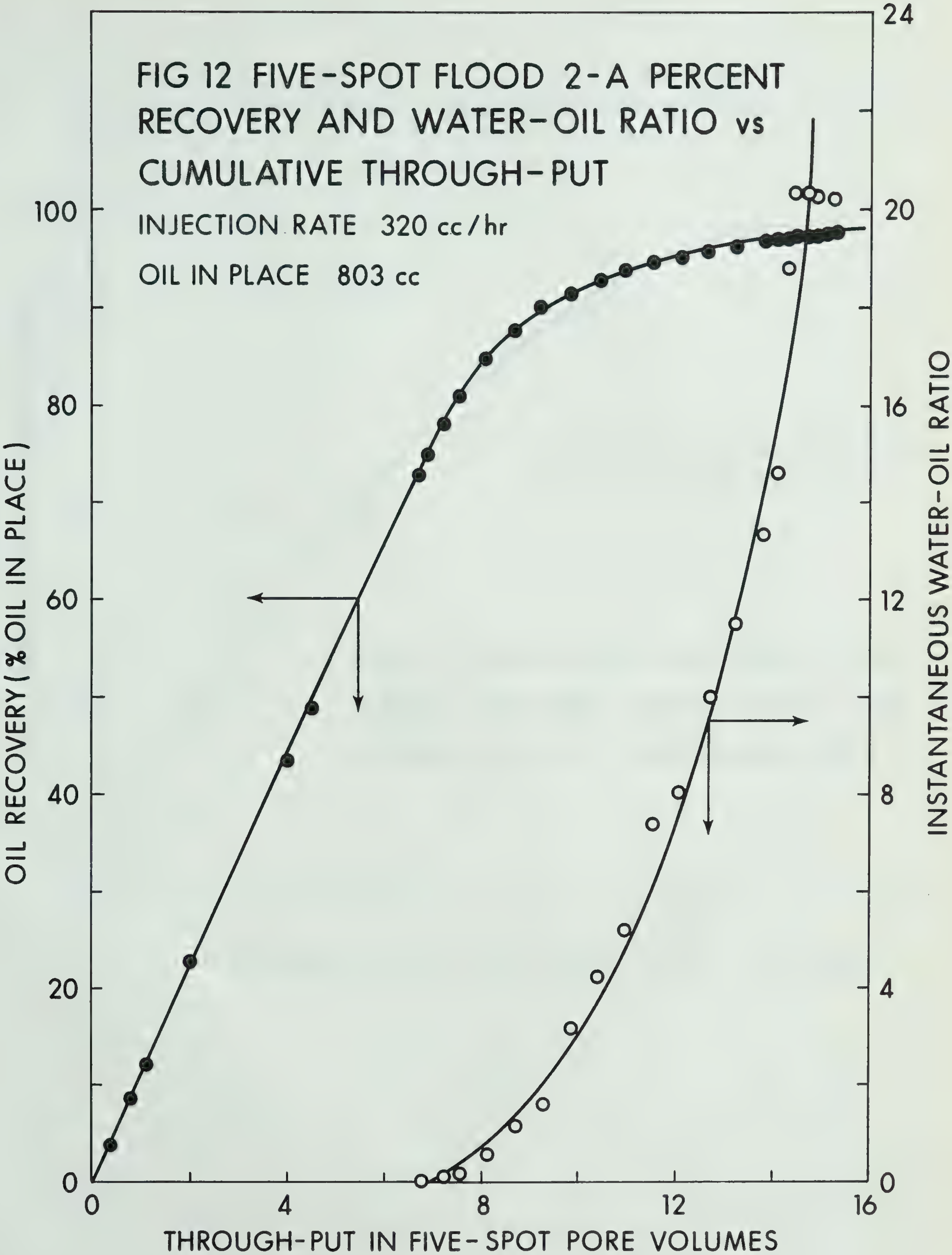


FIG 12 FIVE-SPOT FLOOD 2-A PERCENT RECOVERY AND WATER-OIL RATIO vs CUMULATIVE THROUGH-PUT
INJECTION RATE 320 cc/hr
OIL IN PLACE 803 cc
OIL RECOVERY (% OIL IN PLACE)
INSTANTANEOUS WATER-OIL RATIO
THROUGH-PUT IN FIVE-SPOT PORE VOLUMES
0
20
40
60
80
100
4
8
12
16
24

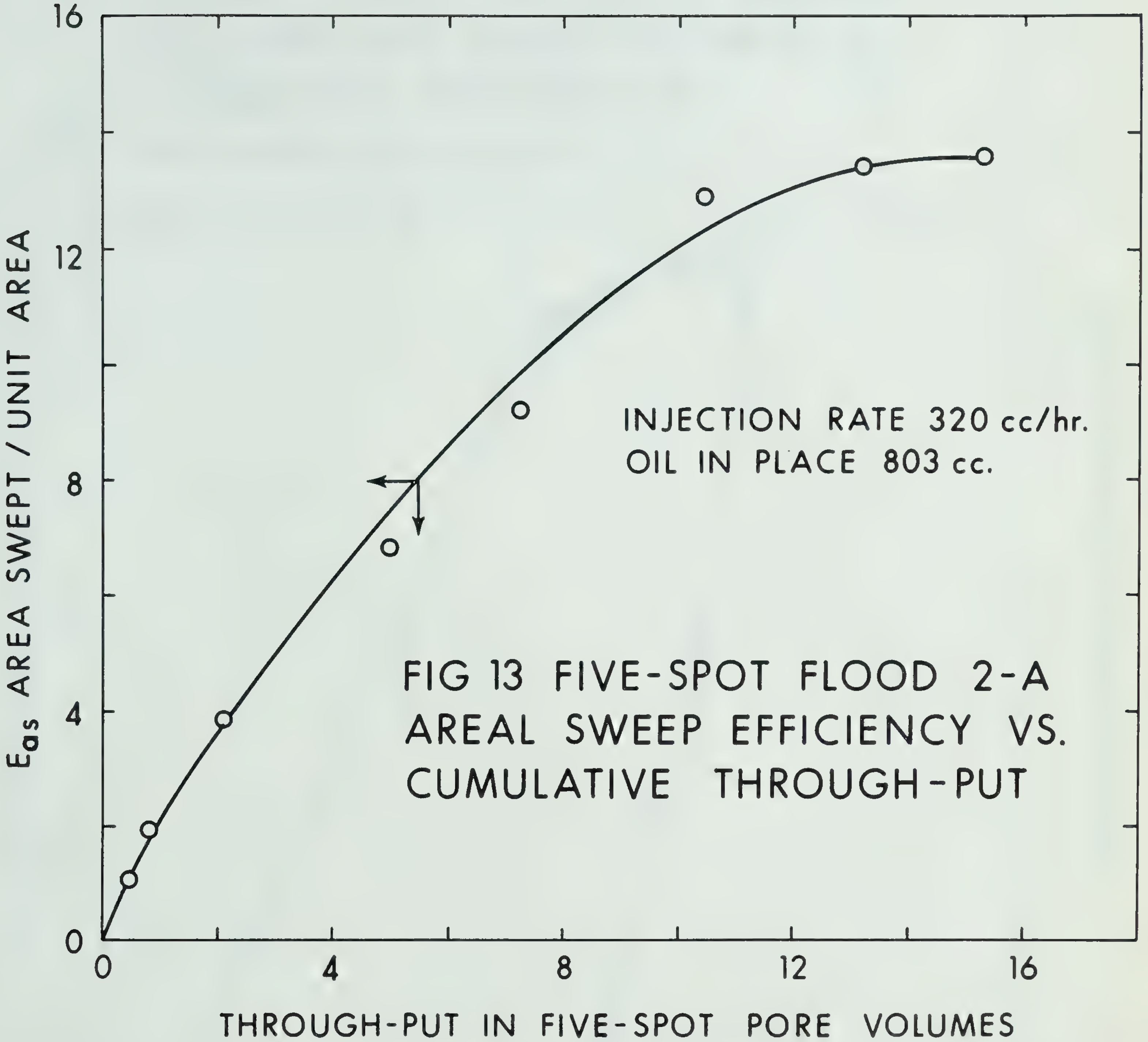


FIG 13 FIVE-SPOT FLOOD 2-A
AREAL SWEEP EFFICIENCY VS.
CUMULATIVE THROUGH-PUT

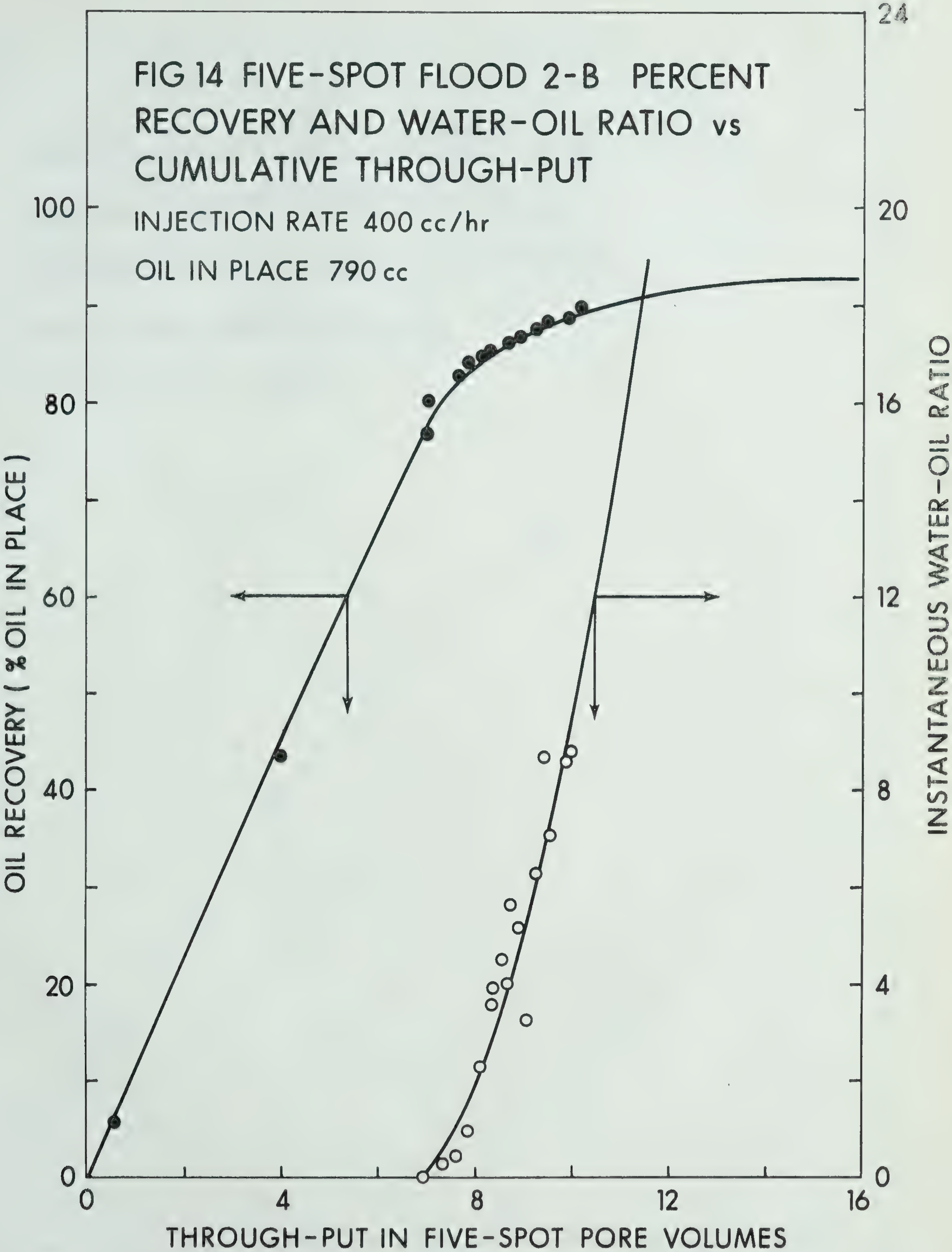


FIG 14 FIVE-SPOT FLOOD 2-B PERCENT RECOVERY AND WATER-OIL RATIO vs CUMULATIVE THROUGH-PUT
INJECTION RATE 400 cc/hr
OIL IN PLACE 790 cc
OIL RECOVERY (% OIL IN PLACE)
INSTANTANEOUS WATER-OIL RATIO
THROUGH-PUT IN FIVE-SPOT PORE VOLUMES
0
20
40
60
80
100
4
8
12
16
24
4
8
12
16
20
0
4
8
12
16

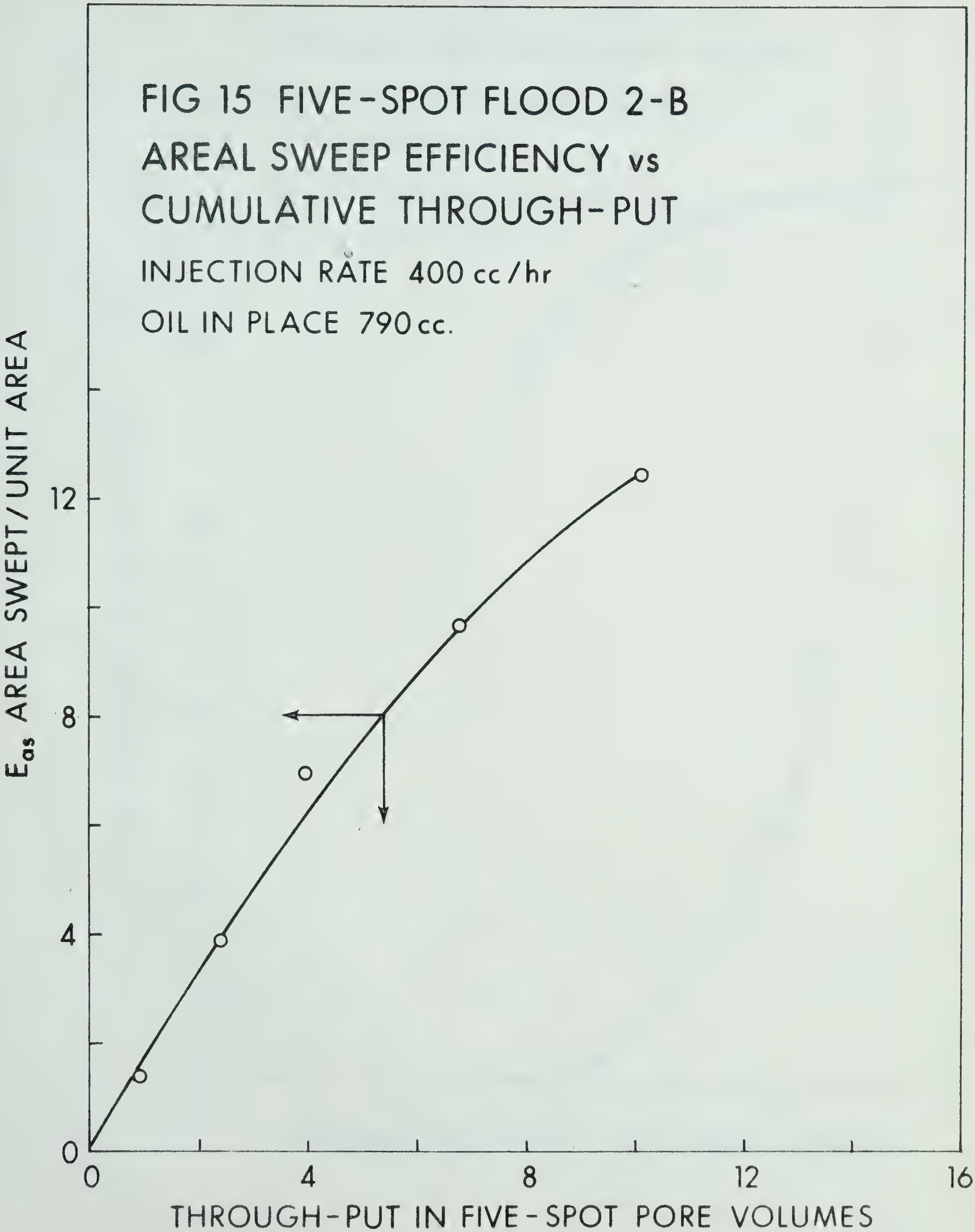


FIG 15 FIVE-SPOT FLOOD 2-B
AREAL SWEEP EFFICIENCY vs
CUMULATIVE THROUGH-PUT
INJECTION RATE 400 cc/hr
OIL IN PLACE 790 cc.
E_{as} AREA SWEPT/UNIT AREA
0
4
8
12
0
4
8
12
16
THROUGH-PUT IN FIVE-SPOT PORE VOLUMES

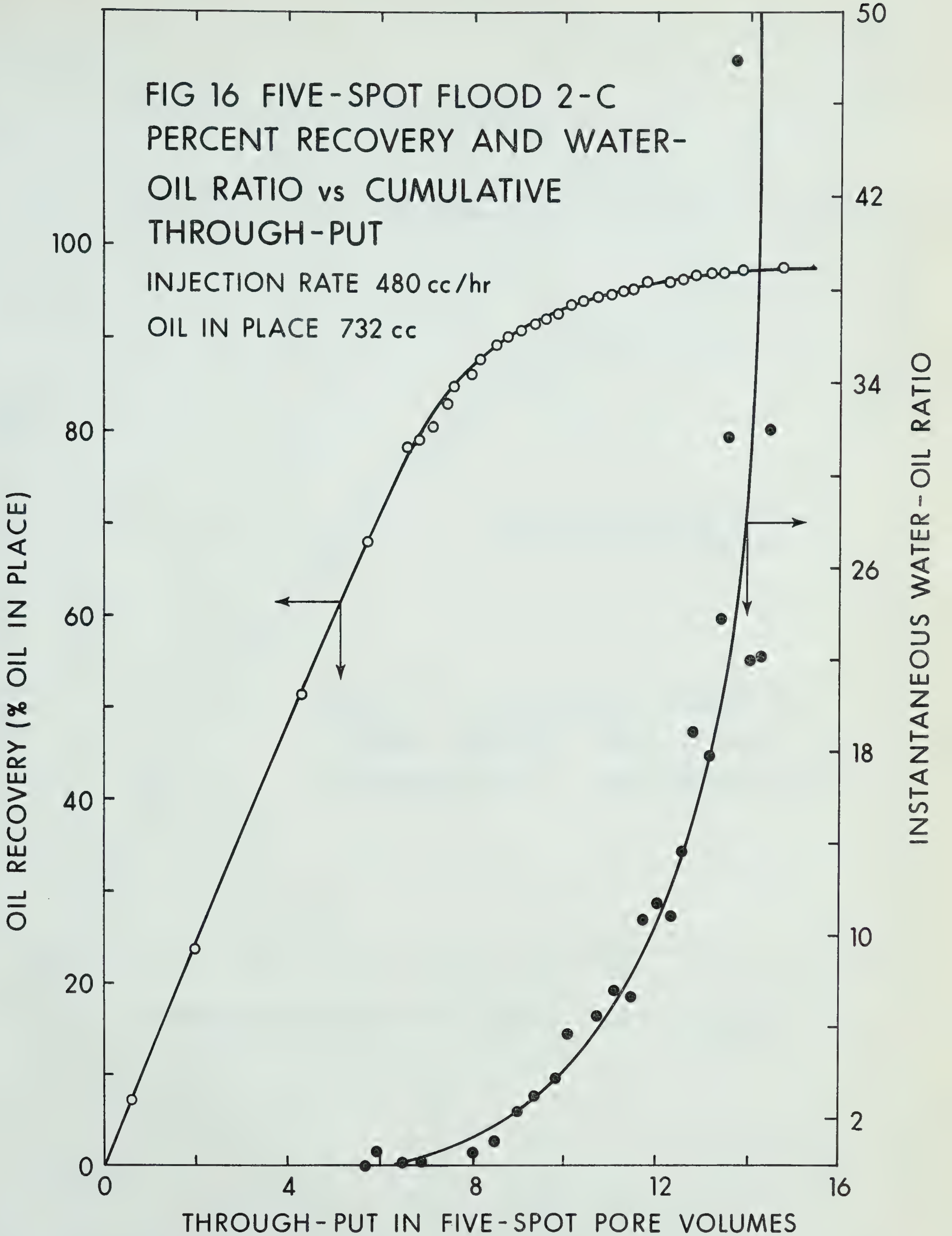


FIG 16 FIVE-SPOT FLOOD 2-C
PERCENT RECOVERY AND WATER-OIL RATIO vs CUMULATIVE THROUGH-PUT
INJECTION RATE 480 cc/hr
OIL IN PLACE 732 cc
OIL RECOVERY (% OIL IN PLACE)
INSTANTANEOUS WATER-OIL RATIO
THROUGH-PUT IN FIVE-SPOT PORE VOLUMES
0
20
40
60
80
100
4
8
12
16
2
10
18
26
34
42
50

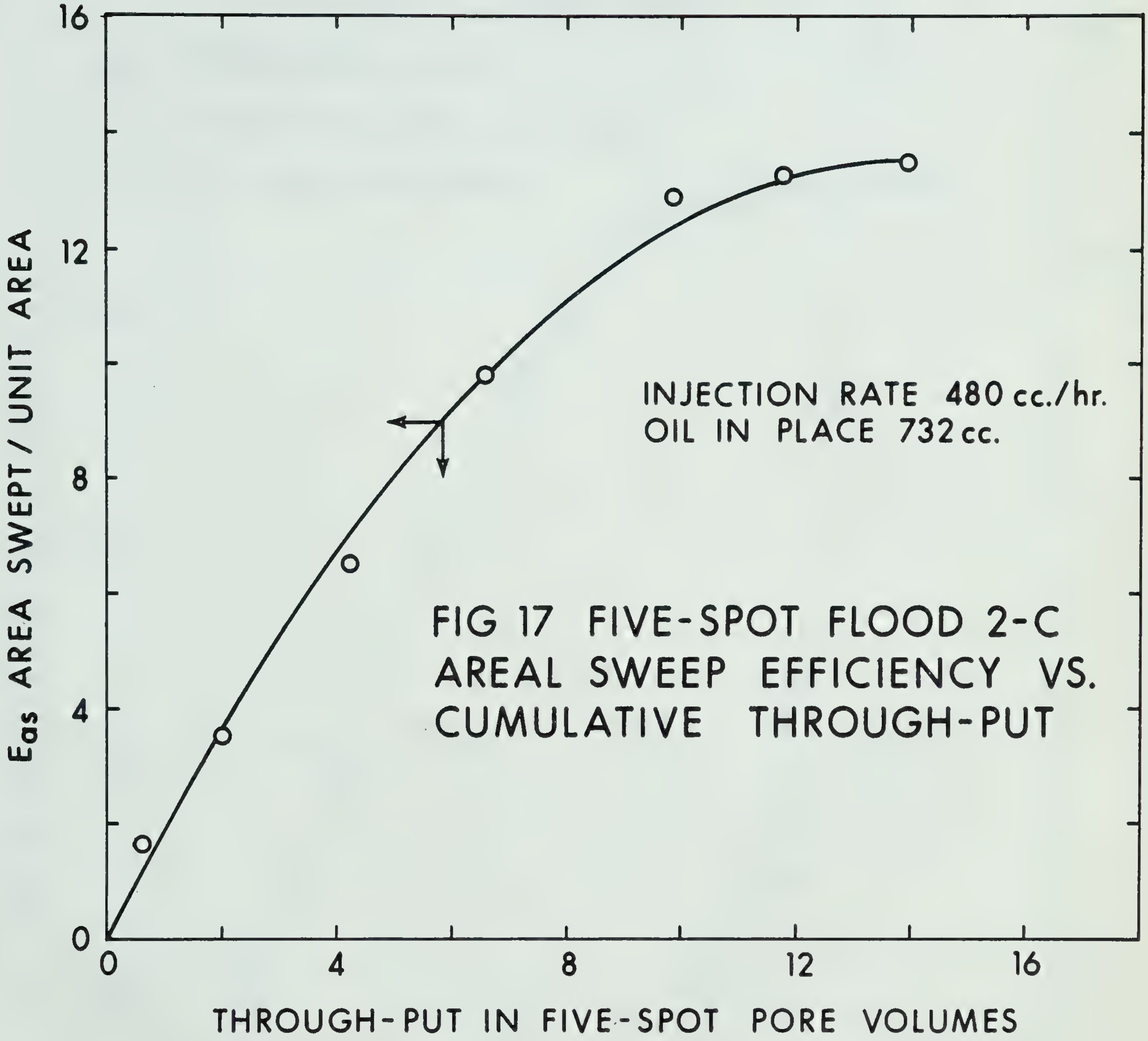


FIG 17 FIVE-SPOT FLOOD 2-C AREAL SWEEP EFFICIENCY VS. CUMULATIVE THROUGH-PUT

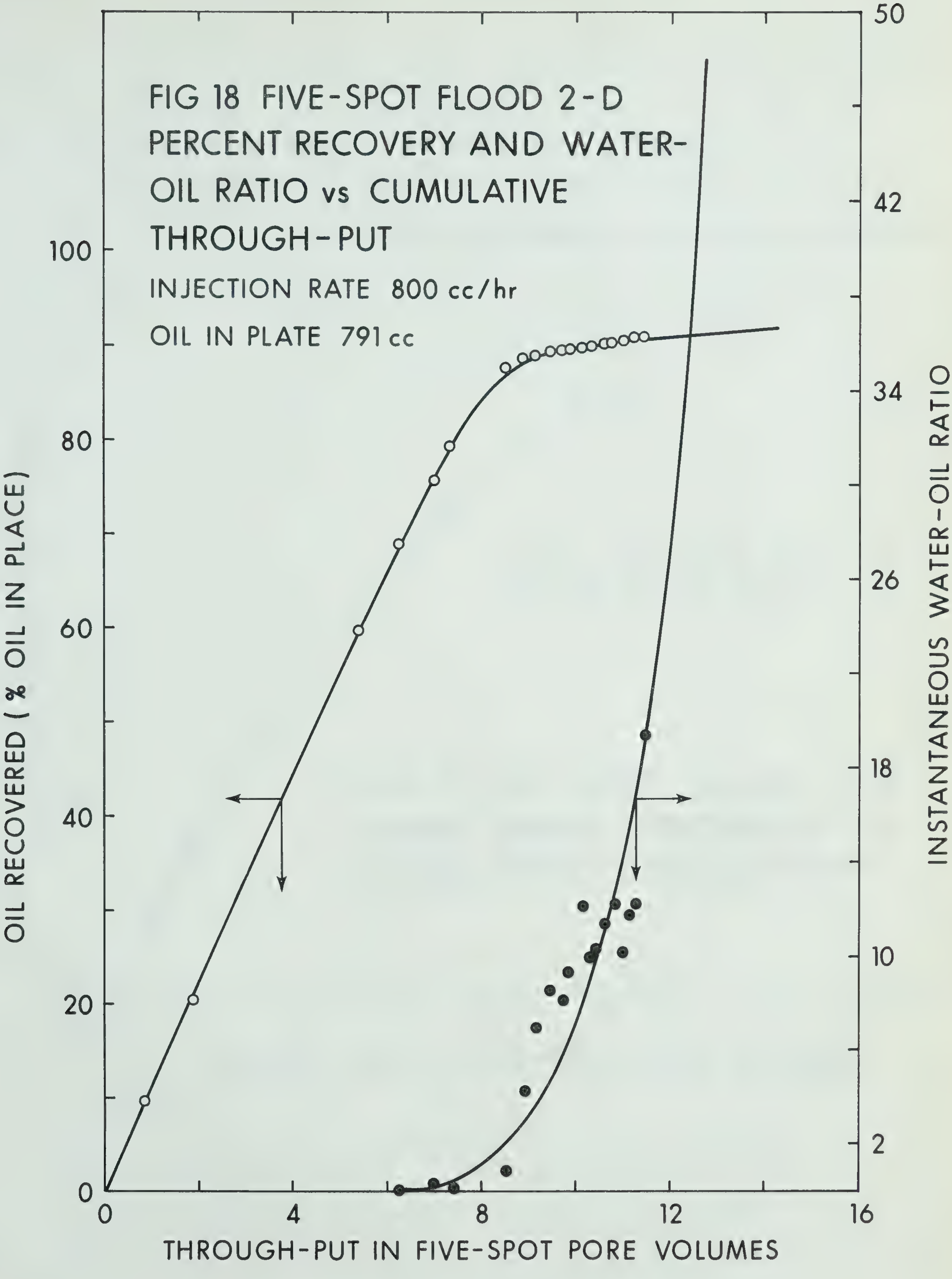


FIG 18 FIVE-SPOT FLOOD 2-D
PERCENT RECOVERY AND WATER-OIL RATIO vs CUMULATIVE THROUGH-PUT
INJECTION RATE 800 cc/hr
OIL IN PLATE 791 cc
OIL RECOVERED (% OIL IN PLACE)
INSTANTANEOUS WATER-OIL RATIO
THROUGH-PUT IN FIVE-SPOT PORE VOLUMES
0
20
40
60
80
100
4
8
12
16
2
10
18
26
34
42
50

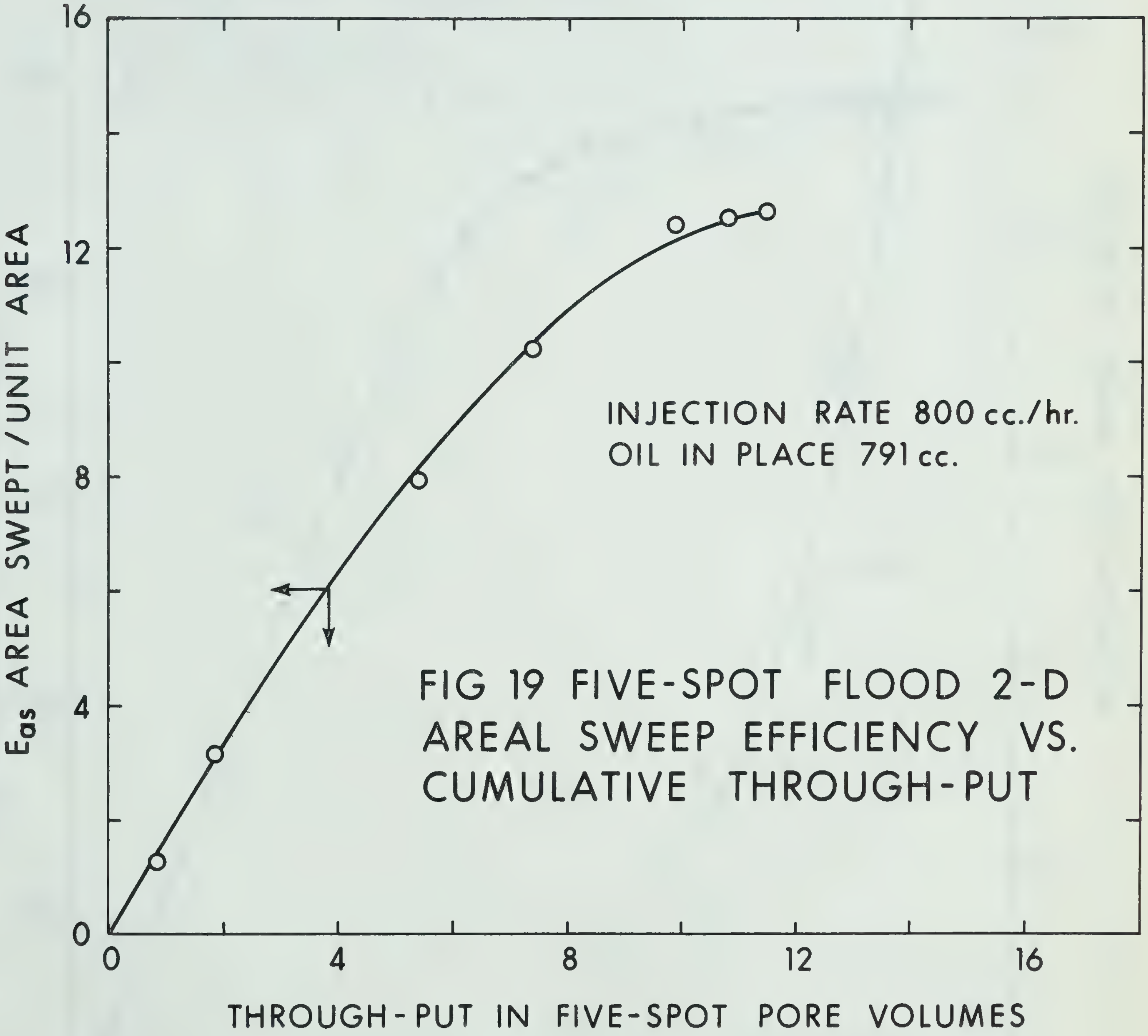


FIG 19 FIVE-SPOT FLOOD 2-D AREAL SWEEP EFFICIENCY VS. CUMULATIVE THROUGH-PUT

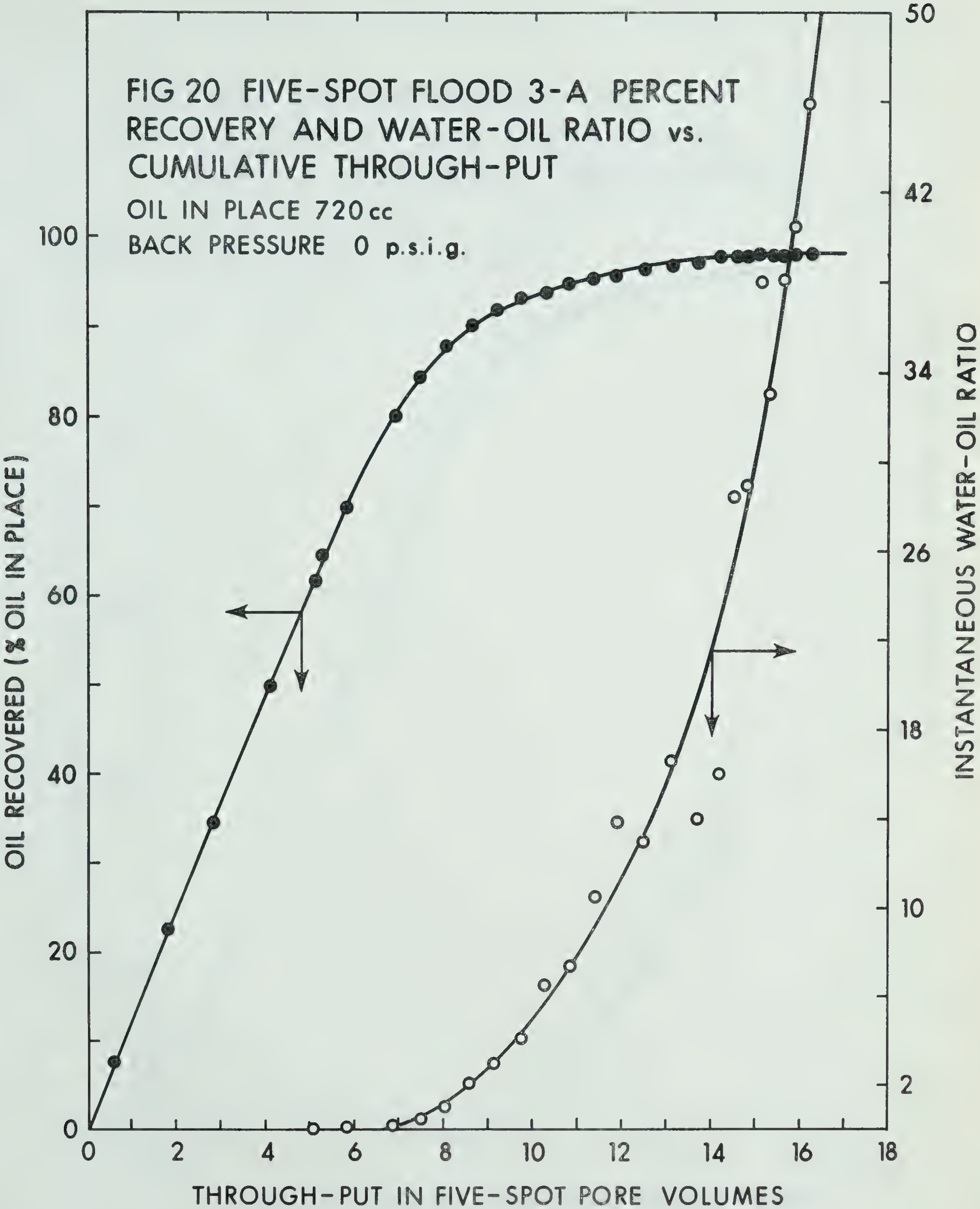


FIG 20 FIVE-SPOT FLOOD 3-A PERCENT RECOVERY AND WATER-OIL RATIO vs. CUMULATIVE THROUGH-PUT
OIL IN PLACE 720 cc
BACK PRESSURE 0 p.s.i.g.
OIL RECOVERED (% OIL IN PLACE)
INSTANTANEOUS WATER-OIL RATIO
THROUGH-PUT IN FIVE-SPOT PORE VOLUMES
0
20
40
60
80
100
2
10
18
26
34
42
50
0
2
4
6
8
10
12
14
16
18

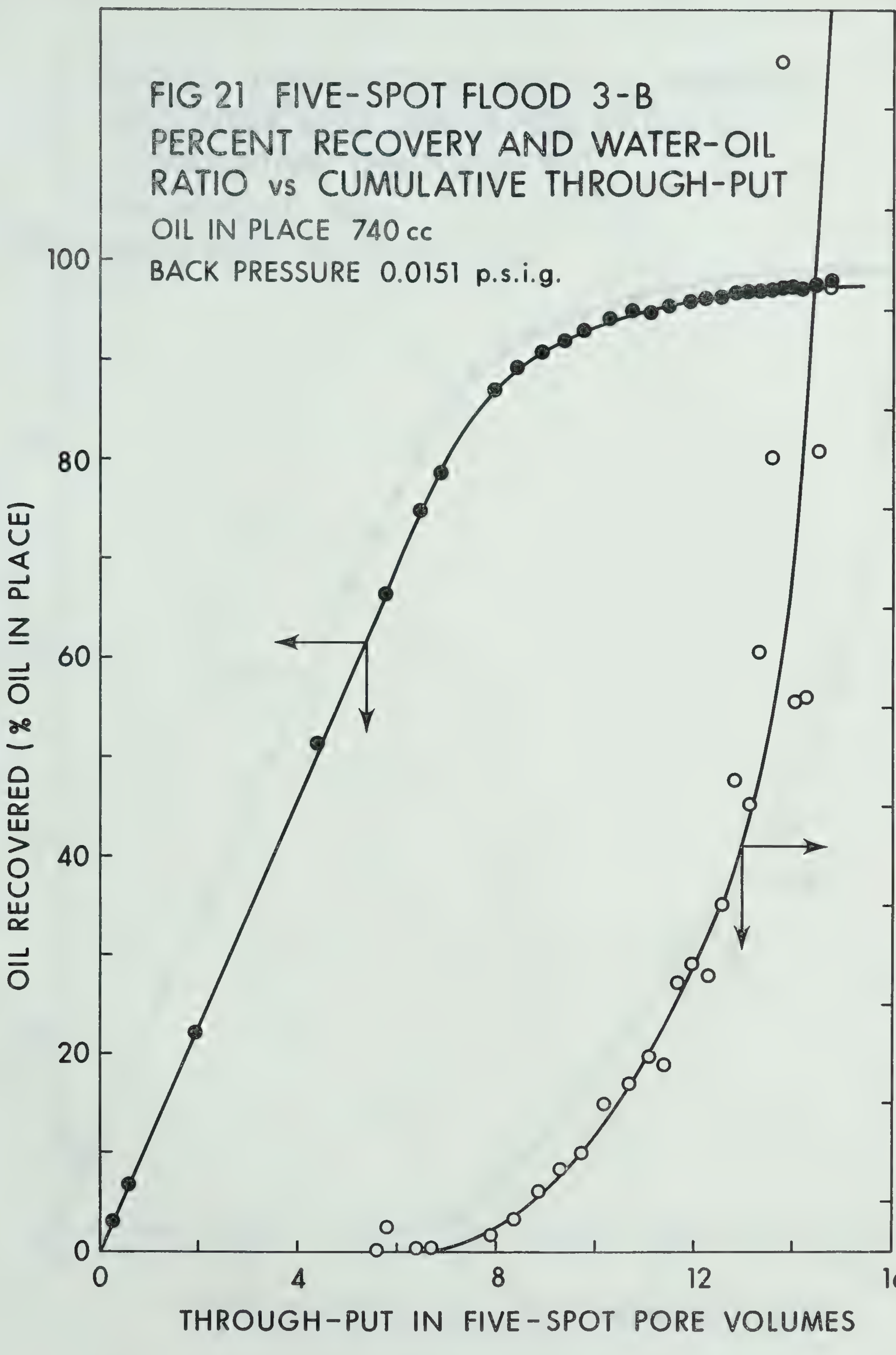


FIG 21 FIVE-SPOT FLOOD 3-B
PERCENT RECOVERY AND WATER-OIL RATIO vs CUMULATIVE THROUGH-PUT
OIL IN PLACE 740 cc
BACK PRESSURE 0.0151 p.s.i.g.
OIL RECOVERED (% OIL IN PLACE)
INSTANTANEOUS WATER-OIL RATIO
THROUGH-PUT IN FIVE-SPOT PORE VOLUMES
0
4
8
12
16
20
40
60
80
100
2
10
18
26
34
42
50

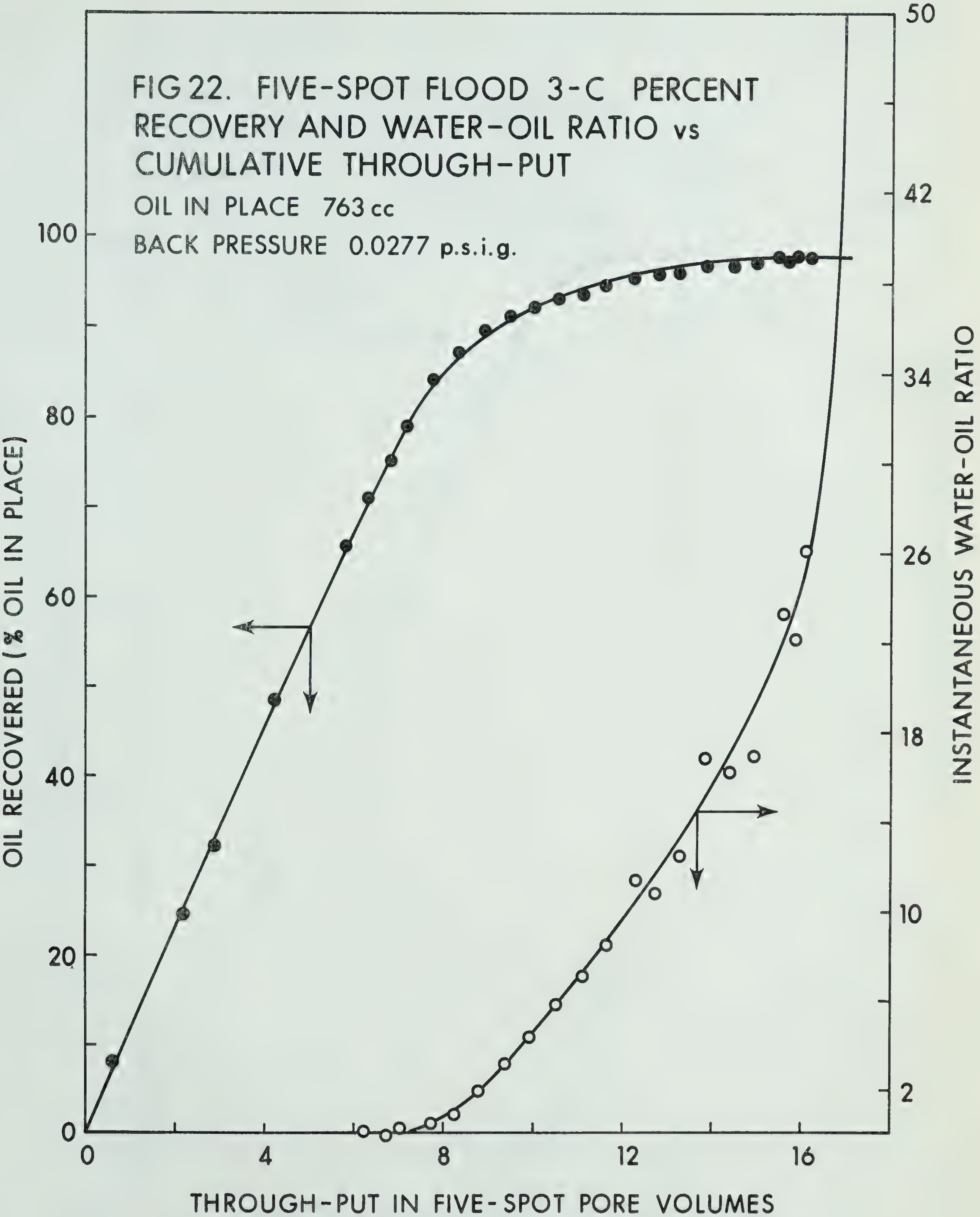


FIG 22. FIVE-SPOT FLOOD 3-C PERCENT RECOVERY AND WATER-OIL RATIO vs CUMULATIVE THROUGH-PUT
OIL IN PLACE 763 cc
BACK PRESSURE 0.0277 p.s.i.g.
OIL RECOVERED (% OIL IN PLACE)
INSTANTANEOUS WATER-OIL RATIO
THROUGH-PUT IN FIVE-SPOT PORE VOLUMES
0
20
40
60
80
100
4
8
12
16
2
10
18
26
34
42
50

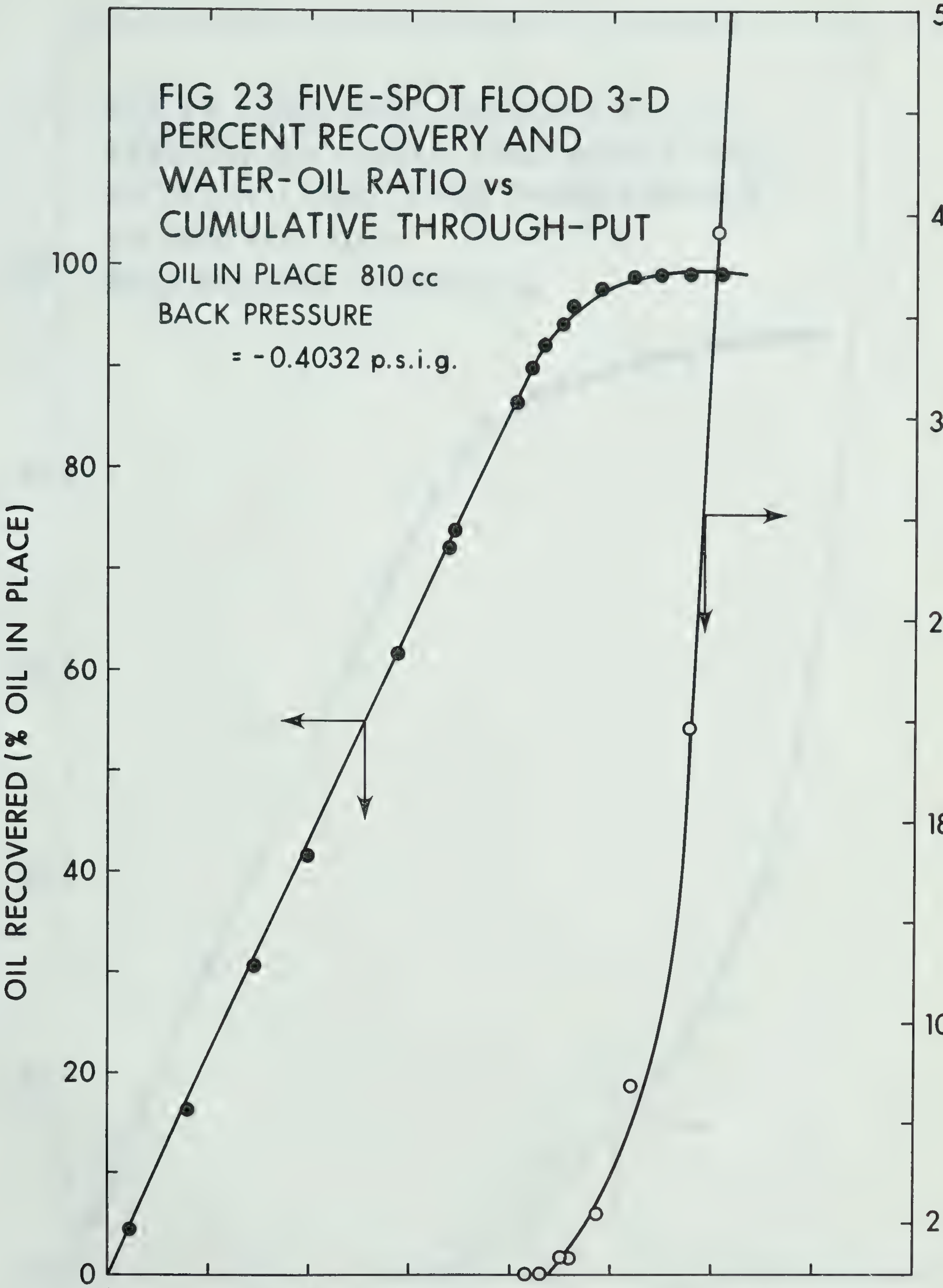


FIG 23 FIVE-SPOT FLOOD 3-D
PERCENT RECOVERY AND
WATER-OIL RATIO vs
CUMULATIVE THROUGH-PUT
OIL IN PLACE 810 cc
BACK PRESSURE
= -0.4032 p.s.i.g.
OIL RECOVERED (% OIL IN PLACE)
INSTANTANEOUS WATER-OIL RATIO
THROUGH-PUT IN FIVE-SPOT PORE VOLUMES
0
20
40
60
80
100
2
10
18
26
34
42
50
0
4
8
12
16

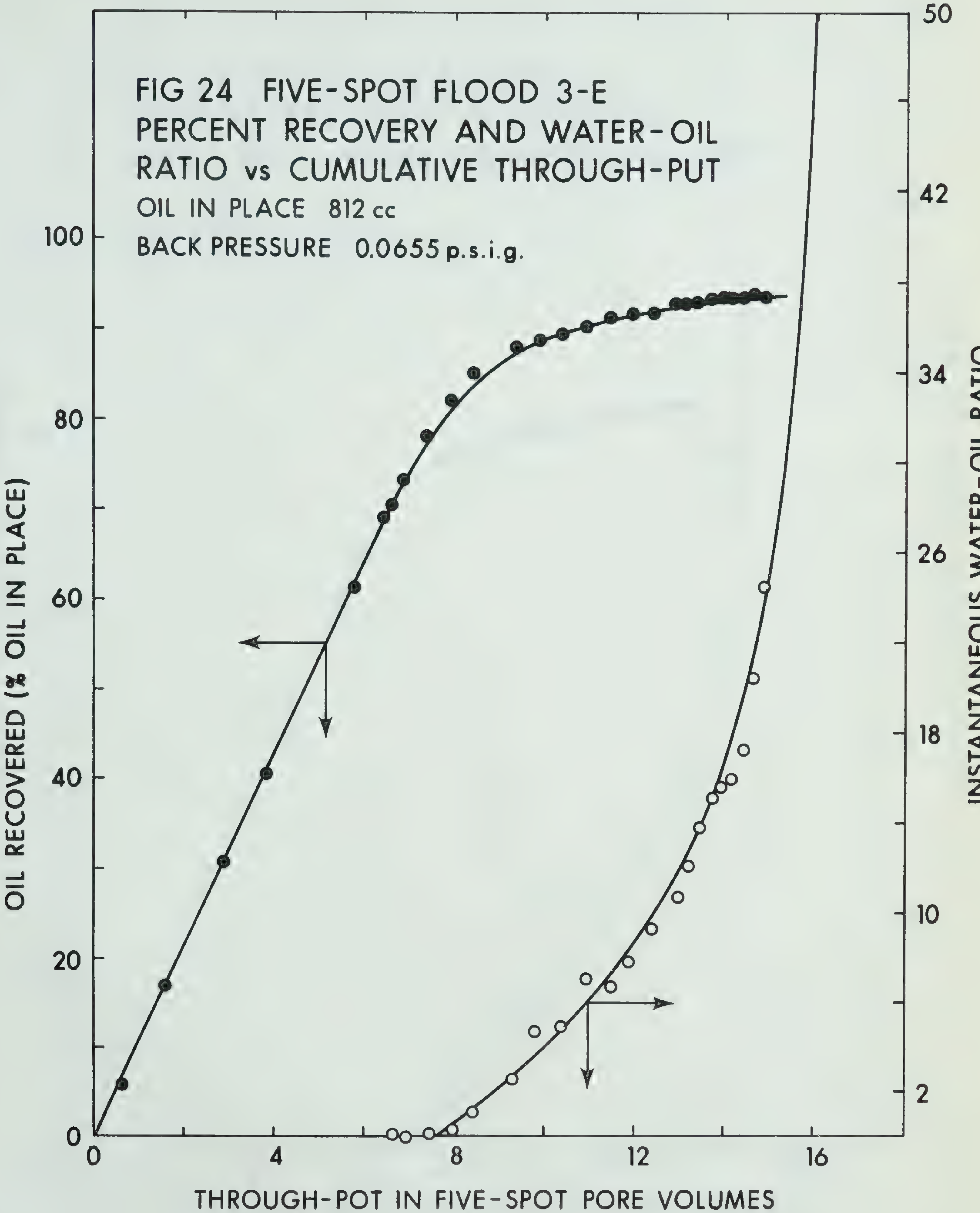


FIG 24 FIVE-SPOT FLOOD 3-E
PERCENT RECOVERY AND WATER-OIL RATIO vs CUMULATIVE THROUGH-PUT
OIL IN PLACE 812 cc
BACK PRESSURE 0.0655 p.s.i.g.
OIL RECOVERED (% OIL IN PLACE)
INSTANTANEOUS WATER-OIL RATIO
THROUGH-POT IN FIVE-SPOT PORE VOLUMES
0
20
40
60
80
100
4
8
12
16
2
10
18
26
34
42
50

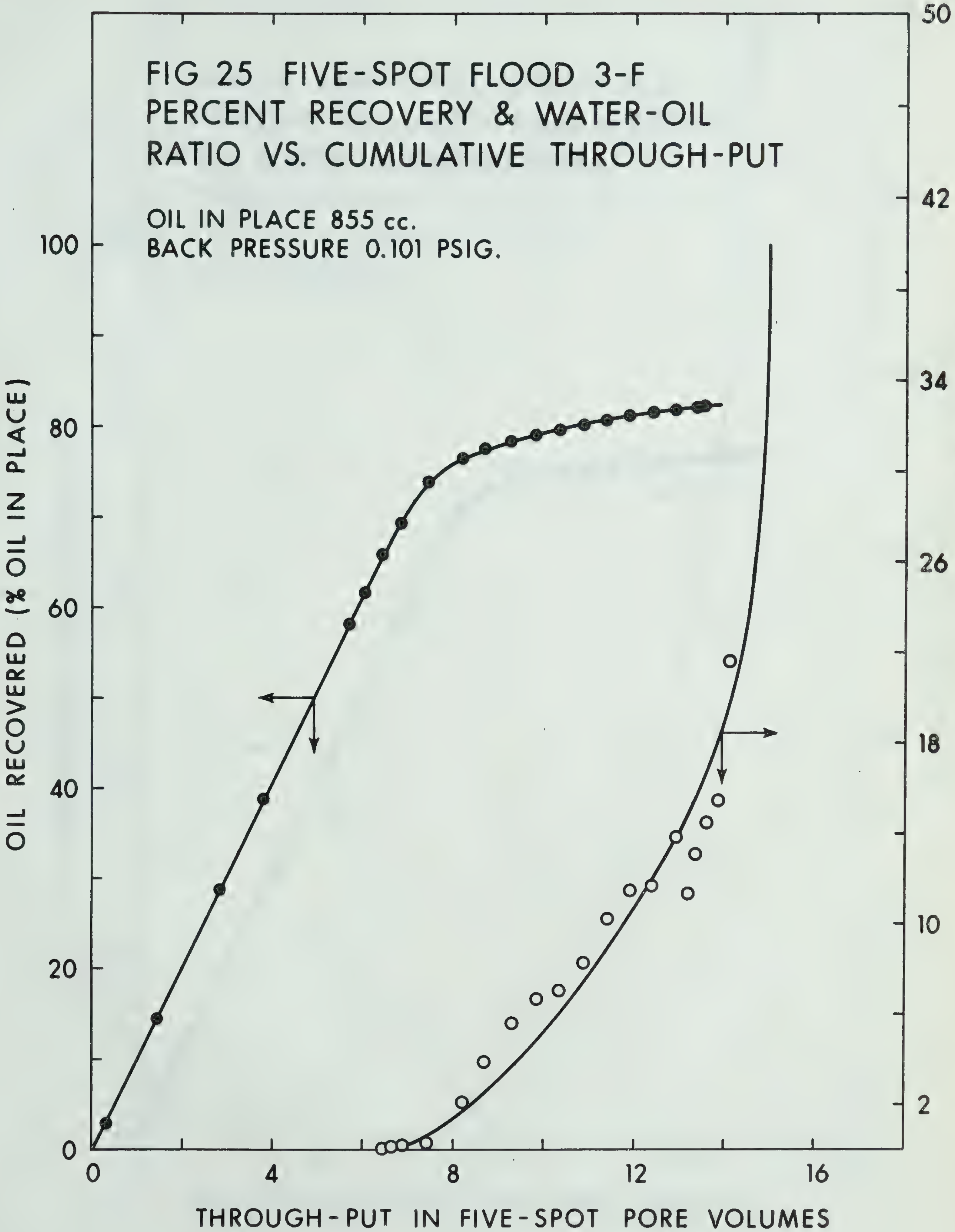


FIG 25 FIVE-SPOT FLOOD 3-F
PERCENT RECOVERY & WATER-OIL
RATIO VS. CUMULATIVE THROUGH-PUT
OIL IN PLACE 855 cc.
BACK PRESSURE 0.101 PSIG.
OIL RECOVERED (% OIL IN PLACE)
INSTANTANEOUS WATER-OIL RATIO
THROUGH-PUT IN FIVE-SPOT PORE VOLUMES
0
20
40
60
80
100
4
8
12
16
2
10
18
26
34
42
50

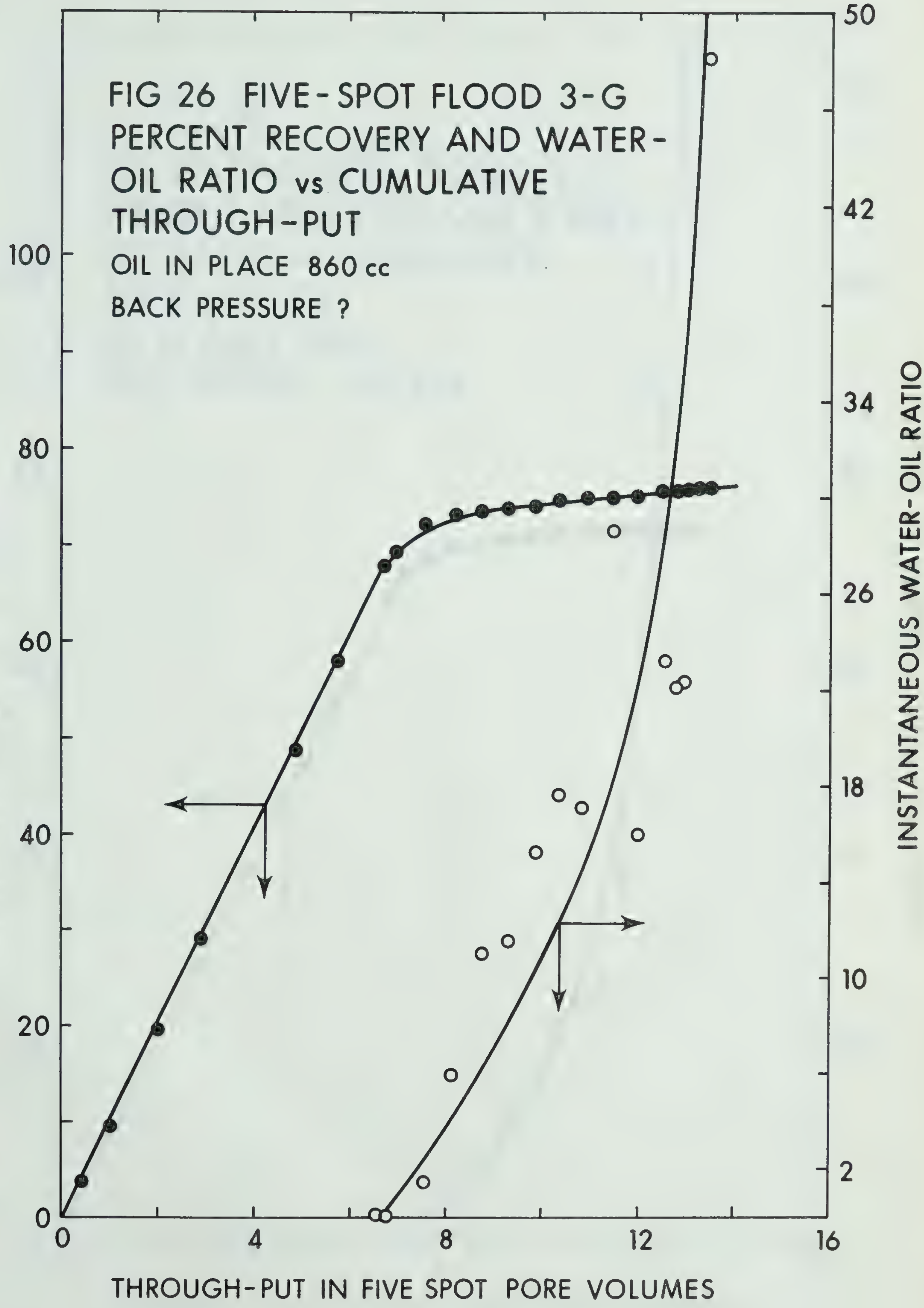


FIG 26 FIVE-SPOT FLOOD 3-G
PERCENT RECOVERY AND WATER-OIL RATIO vs CUMULATIVE THROUGH-PUT
OIL IN PLACE 860 cc
BACK PRESSURE ?
OIL RECOVERED (% OIL IN PLACE)
INSTANTANEOUS WATER-OIL RATIO
THROUGH-PUT IN FIVE SPOT PORE VOLUMES
0
20
40
60
80
100
4
8
12
16
2
10
18
26
34
42
50

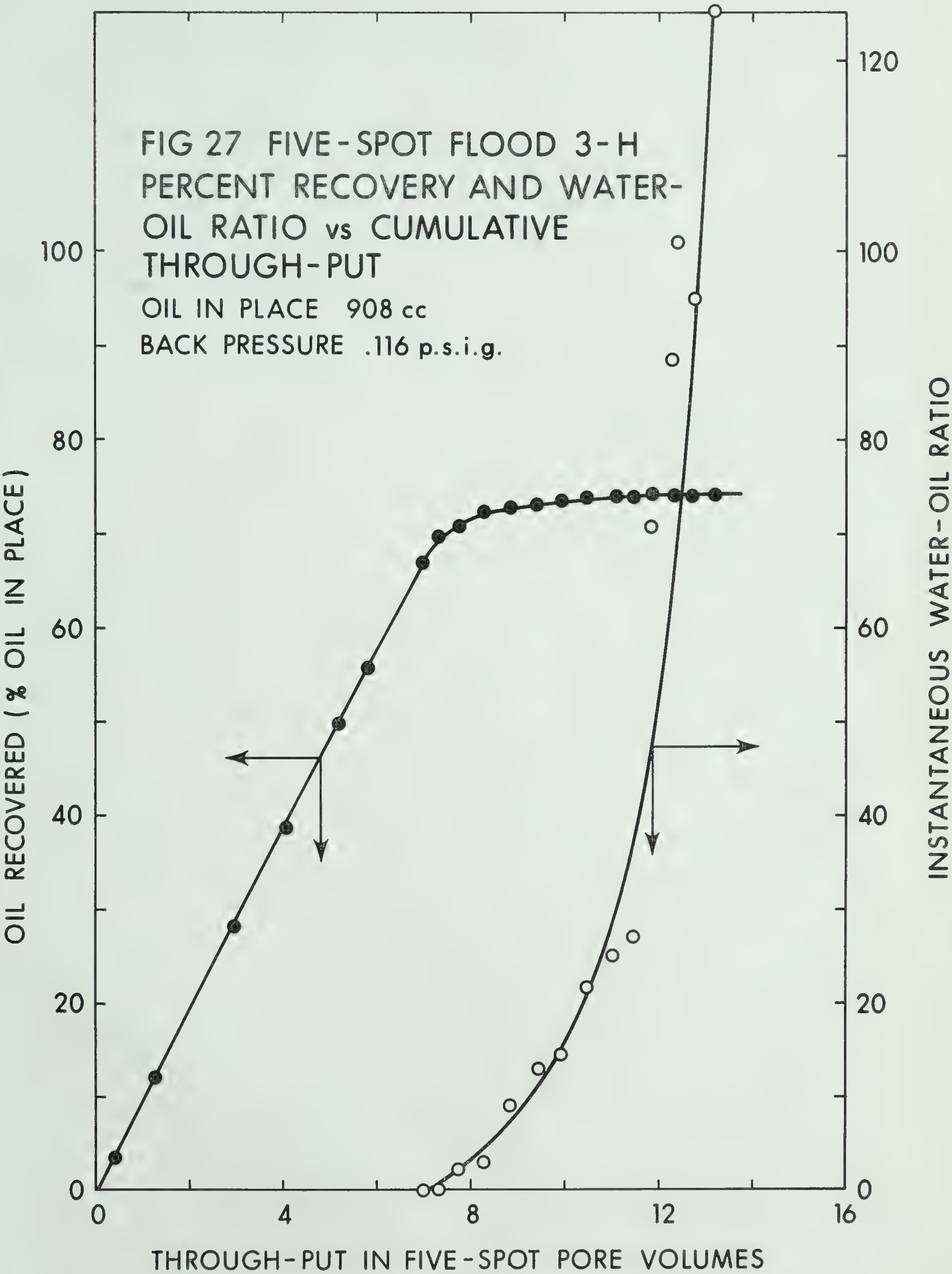


FIG 27 FIVE-SPOT FLOOD 3-H
PERCENT RECOVERY AND WATER-OIL RATIO vs CUMULATIVE THROUGH-PUT
OIL IN PLACE 908 cc
BACK PRESSURE .116 p.s.i.g.
OIL RECOVERED (% OIL IN PLACE)
INSTANTANEOUS WATER-OIL RATIO
THROUGH-PUT IN FIVE-SPOT PORE VOLUMES
0
4
8
12
16
20
40
60
80
100
120